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Journal

of

THE ROYAL AERONAUTICAL SOCIETY

AUGUST 1957

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LONDON

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View of support plate
looking downstream
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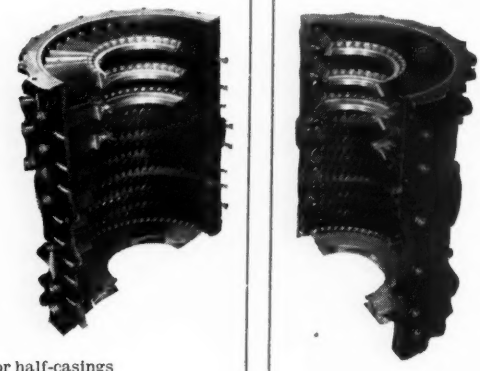

Compressor half-casings
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Journal of
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All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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NOTICES

Wilbur Wright Memorial Lecture, 13th September

The 45th Wilbur Wright Memorial Lecture will be delivered by Dr. Clark B. Millikan, Director of the Guggenheim Aeronautical Laboratory, California Institute of Technology, entitled "Advanced Education and Academic Research in Aeronautics."

The lecture will be held on Friday 13th September 1957 at 6.0 p.m. at the Institution of Civil Engineers, Great George Street, Westminster, S.W.1. Tea will be served at 5.30 p.m.

Some of the Society's Medals and Awards will be presented to the recipients before the lecture.

Sixth Anglo-American Aeronautical Conference

More than 100 delegates from the United States, many of them accompanied by their wives and families, are expected to attend the Sixth Anglo-American Aeronautical Conference. A number of visits to the Aircraft Industry has been arranged for the American delegates, who will also attend the S.B.A.C. Display at Farnborough, before the Conference opens at Folkestone on 9th September. The Conference headquarters will be at the Hotel Metropole and the following is the provisional programme:—

Monday 9th September

Hotel Metropole, 9 a.m. OPENING OF THE CONFERENCE.

Lectures—

9.15–10.45 a.m.—N.A.C.A. Research on V.T.O.L. and S.T.O.L. Aeroplanes, Marion O. McKinney, Jr.

11.00–12.30—Small Nuclear Power Units, Dr. J. V. Dunworth.

2.00–3.30 p.m.—Control of Supersonic Propulsion Systems, John C. Sanders.

4.00–5.30—The Electrical Control of Power Plants, G. M. Sturrock.

EVENING—Conference Reception, Hotel Metropole, 7.00–8.00 p.m.

Tuesday 10th September

Lectures—

9.15–10.45 a.m.—Alleviation of Kinetic Heating Stresses, J. Taylor.

11.00–12.30—Nine Years of Titanium Usage, Leo A. Sharpiro and Emerson LaBombard.

2.00–3.30 p.m.—The Use of High Temperature Non-Metallic Materials, Dr. W. J. Strang.

4.00–5.30—Blast Loading of Aircraft Structures, Professor R. L. Bisplinghoff and Dr. Emmett A. Witmer.

Wednesday 11th September

Lectures—

9.15–10.45 a.m.—Safety in Relation to Structural Damage, Dr. A. E. Russell.

11.00–12.30—An Appraisal of Aeroelasticity in Design, with Special Reference to Aeroelastic Stability, Martin Goland.

2.00–3.30 p.m.—The Presentation of Information by Aircraft Instruments, A. Stratton.

4.00–5.30—Increased Usable Lift through Boundary Layer Control, Charles W. Harper.

EVENING—Reception by The Mayor of Folkestone, Hotel Metropole, 9.00 p.m.

Thursday 12th September

Lectures—

9.15–10.45 a.m.—The Role of Experimental Hyperballistics in the Development of Future Aeroplanes and Missiles, Dr. Herman H. Kurzweg.

11.00–12.30—Design for Repairability of Civil Turbine Engines, A. Harvey-Bailey.

2.00–3.30 p.m.—Aerodynamic Effects of Boundary Layer Unsteadiness, Franklin K. Moore.

4.00–5.30—The Human Pilot as an Aircraft Operator, Sqn. Ldr. T. C. D. Whiteside.

CLOSING REMARKS.

EVENING—CONFERENCE DINNER – DANCE, HOTEL METROPOLE, 7.00 for 7.45 p.m.

Garden Party, 15th September 1957

The Garden Party will again be held at Wisley Aerodrome near Ripley, Surrey, by kind permission of Vickers-Armstrongs (Aircraft) Limited and the Ministry of Supply. The motif of the Garden Party will be light Aircraft and a flying Display will be arranged. There will also be an exhibition of model aircraft and a display of other items in the hangar. Among these items will be a Link D4 Trainer, a model centrifuge, the replica of the original Wilbur Wright engine, which will be shown in working order, and an Alcock and Brown exhibit.

The Garden Party follows at the end of the Anglo-American Conference and it is hoped that most of the American visitors attending the Conference will stay on for the Garden Party.

During the afternoon the Band of Vickers-Armstrongs (Aircraft) Ltd., conducted by Mr. E. R. Howse, will play.

All Members have been sent a separate leaflet giving full particulars of arrangements and transport and an application form for tickets.

Associate Fellowship Examination

The closing date for Candidates in the United Kingdom for the December 1957 Examinations is 31st August. The entry list for those residing abroad closed on the 30th June. Entry forms may be obtained from the Secretary.

News of Members

S. L. Britton (*Associate Fellow*), formerly Chief Project Engineer, is now the Chief Administrative Engineer of Orenda Engines Ltd., Toronto.

J. Bryce (*Associate Fellow*), is now with the English Electric Co. as a Chief Inspector, Development Wing, Stevenage.

P. G. Chaplin (*Associate*), formerly Design Section Leader with Handley Page Ltd., Cricklewood, is now Chief Draughtsman, Weapons Research Division, A. V. Roe and Co. Ltd. at Harrow.

Dr. B. L. Clarkson (*Graduate*), formerly with the de Havilland Aircraft Co. Ltd., has been appointed Sir Alan Cobham Research Fellow in Aeronautics at the University of Southampton.

E. D. C. Cooper (*Associate*) has been appointed Airport Commandant at Hurn.

Squadron Leader H. J. W. Coward (*Associate Fellow*) has retired from the Royal Air Force and has been appointed to the permanent teaching staff of the Llandaff Technical College in Cardiff.

M. C. Curties (*Associate Fellow*) has recently resigned from the R.A.E. to take up an appointment as Instrument Development Engineer in the Project and Development Branch of B.E.A.

Commander L. C. Darling, R.N. (*Associate Fellow*), formerly at the Joint Services Staff College, R.N. Air Station, Culdrose, is now at the Royal Naval Air Station, Arbroath, Angus.

P. T. Fink (*Associate Fellow*) has resigned from his readership at Imperial College and is returning to Australia to take up a readership at the University of Sydney.

Squadron Leader J. Ford (*Associate Fellow*), formerly at R.A.F. Wahn, is now on the Staff of the Flag Officer, Reserve Aircraft, Royal Naval Air Station, Arbroath.

H. FREARSON (*Associate*), formerly with Orenda Engines of Ontario, is now a Quality Control Co-ordinator with the Ryan Aeronautical Company of San Diego, California.

Air Commodore L. R. S. FREESTONE (*Associate Fellow*) has retired from the Royal Air Force and has been appointed Aircraft Sales Manager of I.V. Pressure Controllers Ltd.

A. H. C. GREENWOOD (*Associate Fellow*), formerly Assistant General Manager (Service) at Vickers-Armstrongs (Aircraft) Ltd., is now Deputy General Manager of the Weybridge and Hurn Works.

Wing Commander P. S. HALL (*Associate Fellow*), formerly at No. 2 Officers' Mess, R.A.F. St. Athan, Glamorgan, is now on Technical Staff Duties in H.Q. No. 41 Group, Andover.

D. V. HARRIS (*Graduate*), formerly a Senior Section Leader with the Gloster Aircraft Co. Ltd., is now a Design Engineer in the Air Armament Section, Canadian Westinghouse Co. Ltd., Canada.

C. C. HEAD (*Associate Fellow*), formerly Drafting Officer with I.C.A.O., is now Assistant Secretary of the Air Navigation Commission, I.C.A.O.

W. B. HOUSTON (*Associate Fellow*), formerly Fleet Manager, Britannias, is now Training Manager with British Overseas Airways Corporation.

R. N. HUDSON (*Associate*), formerly a Technical Assistant in the Service Department of Vickers-Armstrongs (Aircraft) Ltd., is now employed by Bristol Aircraft Ltd. as a Technical Representative on Britannia Aircraft.

J. K. HUNT (*Graduate*), formerly Gas Turbine Development Engineer with Armstrong Siddeley Motors Ltd., is now a Gas Turbine Project Engineer with Canadian Pratt and Whitney Aircraft Co. Ltd., Montreal.

Wing Commander W. R. J. MARRIOTT (*Associate*), formerly Senior Technical Officer at R.A.F. Celle, is now Senior Technical Officer at R.A.F. Waterbeach.

R. MIDDLETON (*Associate Fellow*), formerly of Folland Aircraft Ltd., is joining the Aerodynamics Department of Boeing Aircraft, Seattle.

NEWS OF MEMBERS—A CORRECTION

New appointments with the Fairey Aviation Co. Ltd. were given in the June 1957 Journal for T. F. R. GEORGE (*Associate Fellow*), J. D. POOLE (*Graduate*), R. V. READ (*Graduate*) and D. O. SPRATT (*Associate Fellow*), but unfortunately it was not made clear that these appointments were with the Weapons Division of the Company.

DIARY

9th-12th September 1957

Sixth Anglo-American Aeronautical Conference—Folkestone Hotel Metropole.

13th September

45th Wilbur Wright Memorial Lecture "Advanced Education and Academic Research in Aeronautics." Dr. Clark B. Millikan. At the Institution of Civil Engineers, Great George St., S.W.1, at 6 p.m.

15th September

Garden Party, Wisley Aerodrome. 2.30-5.30 p.m.

BRANCHES

24th September

Luton.—Flight Testing the Vulcan. R. J. Falk. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

8th October

Luton.—Human Limitations of High Performance Flight. Sqn./Ldr. T. C. D. Whiteside. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

ACKNOWLEDGMENTS

The Council acknowledge with thanks a copy of "Letters Home from Britain at War 1941," a privately distributed diary written by Franklin H. Joseph, and kindly presented by Major J. Vivian Holman, *Associate Fellow*. Mr. Joseph brought the first Sperry bomb sight to England in April 1941 for the R.A.F. to try out.

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Patrick Alan Amer (*from Graduate*)
James Robert Anderson
Michael Henry Beeching (*from Graduate*)
Johann Francis Chenery
Peter Neville Cornall (*from Graduate*)
Leonard Stanley Davey (*from Graduate*)
Thomas Golding Letten Davis (*from Student*)
George Emerick (*from Graduate*)
Charles Goldberg
Edward James Gregory (*from Associate*)
Peter Francis Locker Hall (*from Graduate*)
Robert Keith Hooks
Alfred Hucknall (*from Graduate*)
Gerald Kenneth Hunt (*from Graduate*)
David George Hurley (*from Graduate*)
Roy Vernon Hurrell (*from Graduate*)
Robert Arthur Basnet James
Alkis Nicholas Lagopoulus (*from Graduate*)
Eckart Lemberg (*from Graduate*)
Ian Hale Lewin (*ex Student*)
Albert Leslie Longhorn
Frank McKenna (*from Associate*)
John Yates Mann (*from Graduate*)
Raj Mohindra (*from Graduate*)
Geoffrey Herbert Nixon (*from Graduate*)
Stanley Gordon Orr (*from Associate*)
Eric Redgrave Owen
Stanley Charles Owers (*from Graduate*)
John Howard Paterson (*from Graduate*)
John Robert George Pearce (*from Associate*)
Peter Alexander Michael Perry (*from Graduate*)
Roy Frederick Plucknett (*from Associate*)
Kenneth Douglas Sadd (*from Student*)
Jonathan Huntley Wallace Shannon (*from Student*)
Ronald Coates Smith (*from Associate*)
Brian Hawley Wager (*from Graduate*)
Ronald Stuart Wambeek
Francis Robert Ward (*from Graduate*)
Michael Henry Lewin Waters (*from Graduate*)
Rex Maddock Whalley (*from Graduate*)
Alan Wilding (*from Graduate*)
Ian Armstrong Wilkinson (*from Graduate*)
Albert Edward Williams (*from Associate*)

Associates

Joseph Frankland Burrow
Charles Chappell
Eric Henry Crudden (*ex Student*)
Ronald Leonard Dack (*from Student*)
Joseph Anthony Kenneth De Croos
Albert James Doble
Victor Jack Glanville
Angus Dean Howarth
Dennis Hughes
Peter James Jones
Kishor Kanayalal Kirtikar (*from Graduate*)
James Law
David Lockspeiser
William McKnight
John Alexander Blackhall Ogilvie
Alfred Payne (*ex Student*)
Hugh Cecil Rose
Ronald Geoffrey Sheppard
Stanislaw Wojciech Wesolowski
Sydney Wrightson

Graduates

Anthony Trevor Atkins
Robert George Bell
James Anthony Machell Kennerley
Coimbatore Sambamoorthi Krishnamoorthi (*from Student*)
John Geoffrey Rowland Osborn
Dennis Michael Reader
Sidney John Swadling (*from Student*)
David Wilkinson

Students

Richard Marshall Berry
Geoffrey Alan Bunce
John Robert Stewart Davidson
Edward Nicholas Davies
Michael Edward Doughty
Barry John Dukes
Keith Hobbs
Daljit Singh Madan
Om Prakash Mal
Patrick John Manley
Kenneth Bernard Marsh
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William Meadowcroft
Clive Gordon Milner
David James Priest
Joan Elizabeth Randall
John Edward Rose
Paul Stallard
Joseph Barrymore Swainston
Michael Ward

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Edward Colin Selby Little

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 61 AUGUST 1957 NUMBER 560

Synthetic Aids to Flying Training

by

W. MAKINSON, M.Sc., A.M.I.E.E. and G. M. HELLINGS, B.A., A.F.R.Ae.S.

(Managing Director and Chief Engineer, Air Trainers Link Limited)

The 1025th Lecture to be given before the Society and the 28th Main Lecture to be held at a Branch of the Society was held under the auspices of the Halton Branch on 7th February 1957. The Lecture "Synthetic Aids to Flying Training" was given by Mr. W. Makinson, M.Sc., A.M.I.E.E. and Mr. G. M. Hellings, B.A., A.F.R.Ae.S. Group Captain A. K. Hunter, O.B.E., A.F.R.Ae.S., Chairman of the Halton Branch, opened the meeting before handing over to Mr. E. T. Jones, C.B., O.B.E., M.Eng., F.R.Ae.S.

Group Captain A. K. Hunter, O.B.E., A.F.R.Ae.S., Chairman of the Halton Branch:—The Halton Branch had the pleasure and privilege that evening of providing the setting for a Main Society Lecture and he would like to extend to the President, and to the officials of the Society who were with them that evening, a most cordial welcome, and also to those visitors from neighbouring Branches and their guests from Bomber Command.

The President of the Society Mr. Jones, needed no introduction. He was well known to them all, from his long association with research and development activities in the Ministry of Supply and its establishments. But apart from his office as President, it was most fitting that he should be in the Chair because his association with aviation extended way back to the beginning, almost, and his connections had not been solely those of research and development. He started in a very practical way as a pilot and an instructor in the R.F.C. and the early days of the R.A.F. when aids, synthetic or otherwise, were practically unknown and therefore he could view this subject as one who had seen aids, of any sort, develop from nothing to the present state of complication and efficiency.

He would ask the President to take over the proceedings. E. T. Jones, C.B., O.B.E., M.Eng., F.R.Ae.S.: This was the First Main Lecture of the Society to be held at the Halton Branch and in this respect the evening was an historical one.

The practice of holding Main Lectures at Branches was started in 1948 and in all some two dozen Main Lectures had now been spread between the 27 Branches of the Society.

Being the First Main Lecture held at the Halton Branch it was fitting that the subject was one which fitted the aeronautical environment of the district and it gave him great pleasure to note that the lecturers also were in the midst of the same environment.

Some of them might think that synthetic aids to flying training started with the advent of the "Link trainer" but while this machine started a new age in training devices, synthetic aids to operational flying went back to the First World War.

Now it was his pleasant duty to introduce the lecturers but as they were both well known he could be brief.

Mr. Makinson first became prominent when he took charge of the Blind Landing Experimental Unit in 1951 and it was no doubt his experience in that unit that drew his attention to the need for synthetic training devices. Between 1954 and 1956 he was the Ministry of Supply scientist at the Ministry of Defence and for the past year he had been Managing Director of Air Trainers Link Ltd.

Mr. Hellings was initially in practice as a Patent Consultant and for one year was engaged on helicopter design. After seven years in the Ministry of Supply he joined Air Trainers Link Ltd. in 1949 and he had for a long time been Chief Engineer there.

Clearly there were no people better qualified to give a lecture on Synthetic Training Devices and he would now call upon Mr. Makinson and Mr. Hellings to deliver their joint paper.

1. Introduction

The piloted aircraft provides the supreme example of the highly complex machine performing a precise function in which the control loop is still completed through a human operator. Although both physically and mentally his task has been greatly assisted by the introduction of automatic pilots, auto-stabilisers, power controls, flight directors and the like, he still possesses the ultimate advantage over the machine of being able to use judgment in the face of arbitrarily changing circumstances. Thus, until it is possible in advance to define the required tasks exactly, and to measure the subsequent performance of the system in precise and unambiguous terms, the pilot will be saved from the encroachment of automation.

The performance of the human operator is described by the aptness and speed of his reaction to the pertinent stimuli, in effect his transfer function as an integral element of the overall control loop. This transfer function for a repetitive task is greatly improved by learning, hence the emphasis placed on air crew training by both military and civil authorities.

Economic and practical considerations demand that full use be made of synthetic aids at all stages of the training programme, ranging from animated models and procedure trainers at one end of the scale to the full flight simulator at the other. The use of such training aids is now universally accepted and the requirement for pre-flight instruction in emergency procedures is accentuated by modern developments in aviation which have brought in an era where errors of skill or judgment can seldom be repeated.

The story of the development of flying training devices is almost as fascinating as that of flying itself and progress has been equally rapid. Of the early pioneers in this field one name at least, that of Link, has survived to be associated today with the most forward thinking in flight simulation. Many others have contributed substantially, notably those responsible for the great advances made in analogue computing

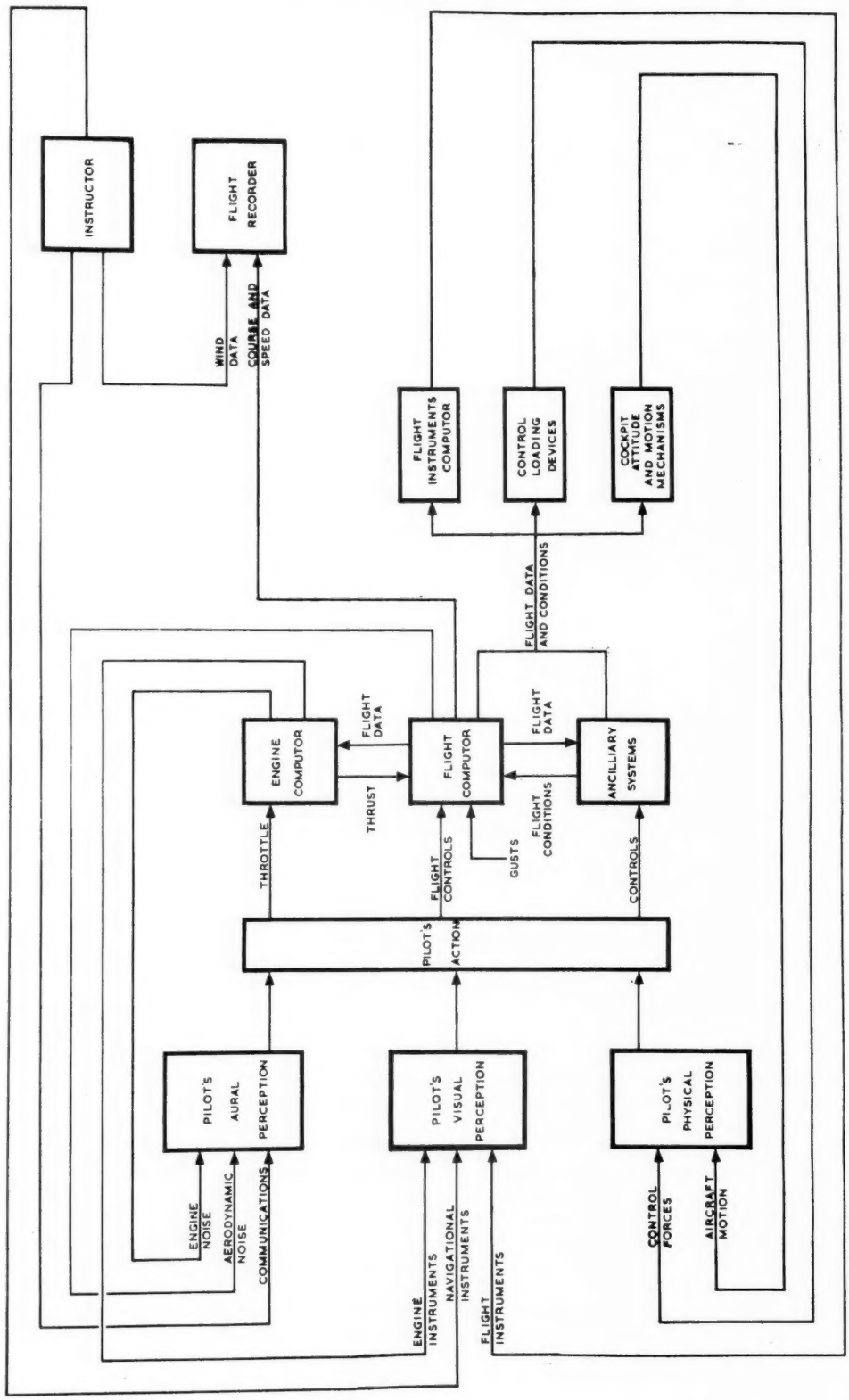


FIGURE 1. Basic simulated control loops.

techniques both during and since the Second World War.

A number of papers[1, 2, 3] published in recent years, including that of Ringham and Cutler[4] published in the JOURNAL of the Society, have dealt with the basic principles and technical problems of the flight simulator and have discussed its economic and practical advantages over full-scale training methods. The object here is to trace the development of some of the techniques currently used in the handling side of the trainers and, to outline further refinements now being considered.

Although recent advances tend naturally to apply mainly to the full flight simulator, it does not follow that earlier methods have become obsolete. On the contrary, where the specific training requirements allow for simplification or generalisation of other related functions, these less complex approaches can be used with advantage. Most of the techniques described still have their place in the wide range of training devices now available to the civil or military user.

2. Basic Requirements

In essence the trainer, whatever its purpose, will have to compute the behaviour of the aircraft resulting from pilot action and external disturbances, exhibit this information to the air crew via such instruments and sensory effects as are normally available in flight and at the same time provide a permanent record of the exercise with sufficient detail and accuracy to enable the performance of the trainee to be assessed.

Figure 1 illustrates in schematic form the information sources and control loops involved in an elementary flight trainer. The cockpit controls provide the input to the computing elements which, from the information provided, determine the resultant attitude, speed, etc., in a manner consistent with flight conditions. The engine computer will, from control displacements and flight data, derive an appropriate thrust which, when supplied to the flight computer, results in forward speed along the selected flight path. This computer, in turn, produces course and speed data which is supplied to a recorder unit to form a record of the flight for the instructor's information and for post-flight discussion.

At the same time flight data is distributed, as required, to further systems actuating the cockpit instruments, the control loading devices and the cockpit attitude mechanisms. With realistic noise reproduction in the trainer cockpit, the information produced from these sources results in the pilot becoming visually, physically and aurally aware of the demands made upon him by the system of which he is an integral part.

Usually, provision will be made for the inclusion of external disturbances such as gusts, and for the introduction by the instructor of flight emergencies and failures demanding the appropriate corrective action.

The exact nature of the training requirement governs the technical specification of such a trainer; the more restricted the object of the equipment, the easier will it be to simplify it in other aspects. For instance, if merely pre-flight cockpit drill is to be taught, although it will be necessary to preserve the external appearance and layout of the cockpit accurately, only the interrelated performance of switches, instruments, etc., need be reproduced and the majority of the computer circuits omitted. If radio or navigational procedures are the object of the training, then at least a simple flight computer and flight control system will be required to generate the translatory information which, in its turn, must activate the radio and navigational instruments in an appropriate manner. Finally, when an operation calling for very precise flying, such as an interception or an instrument approach and landing is to be rehearsed, all the pertinent visual, aural and physical sensations involved in this operation with a fully representative control system and flight computer will be needed.

In the flight simulator used for aircraft type conversions, periodic proficiency checks and instrument rating renewals, it may be necessary to satisfy all the foregoing requirements simultaneously. In this case, the provision of the appropriate computing elements and transfer of information between them becomes a complex matter. This is indicated in Fig 2 which shows the routing of information between the three basic units of a simulator for a modern military aircraft, namely the cockpit unit, the instructor's console and the computer rack.

3. The Link Vacuum-Operated Trainers

Just before the Second World War the use of synthetic flying trainers was given a substantial boost by the introduction of the Link blind-flying trainer manufactured and distributed by the Link organisation of America. Subsequently, the company now known as Air Trainers Link Ltd., became responsible for the importation, overhaul and servicing of these trainers and was eventually licensed to produce in Great Britain models suited to U.K. requirements and components, but maintaining the same principles of operation. This Link 'D' type trainer is shown in Fig. 3.

These equipments were largely vacuum-operated, although mechanical, electrical and electronic actuating elements are also employed. The fuselage, mounted on a universal joint, responded to the controls with realistic motion about the three flight axes, the angular rates being proportional to control displacements, with suitable time lags in response. Cockpit attitude was used directly to actuate certain of the flight instruments. Weather-cocking, mushing and stalling were also simulated. A "crab" type plotting table provided a record of ground track. With the addition of the radio and navigation equipment of its day, "the Link" became an integral part of the R.A.F.'s accelerated training programme.

The methods used in computing flight data were essentially empirical. For example, a simplified illustration of the pitch/air speed system used is seen in Fig. 4. Air speed, as computed, is proportional to the degree of exhaustion of the bellows which is connected, through a controllable valve, to an exhaust pump and has in its supply line an adjustable bleed '*K*' to atmosphere. The final equilibrium position of the bellows is thus a function of the setting of the valve. The influence of the throttle on indicated air speed is inserted at the lever

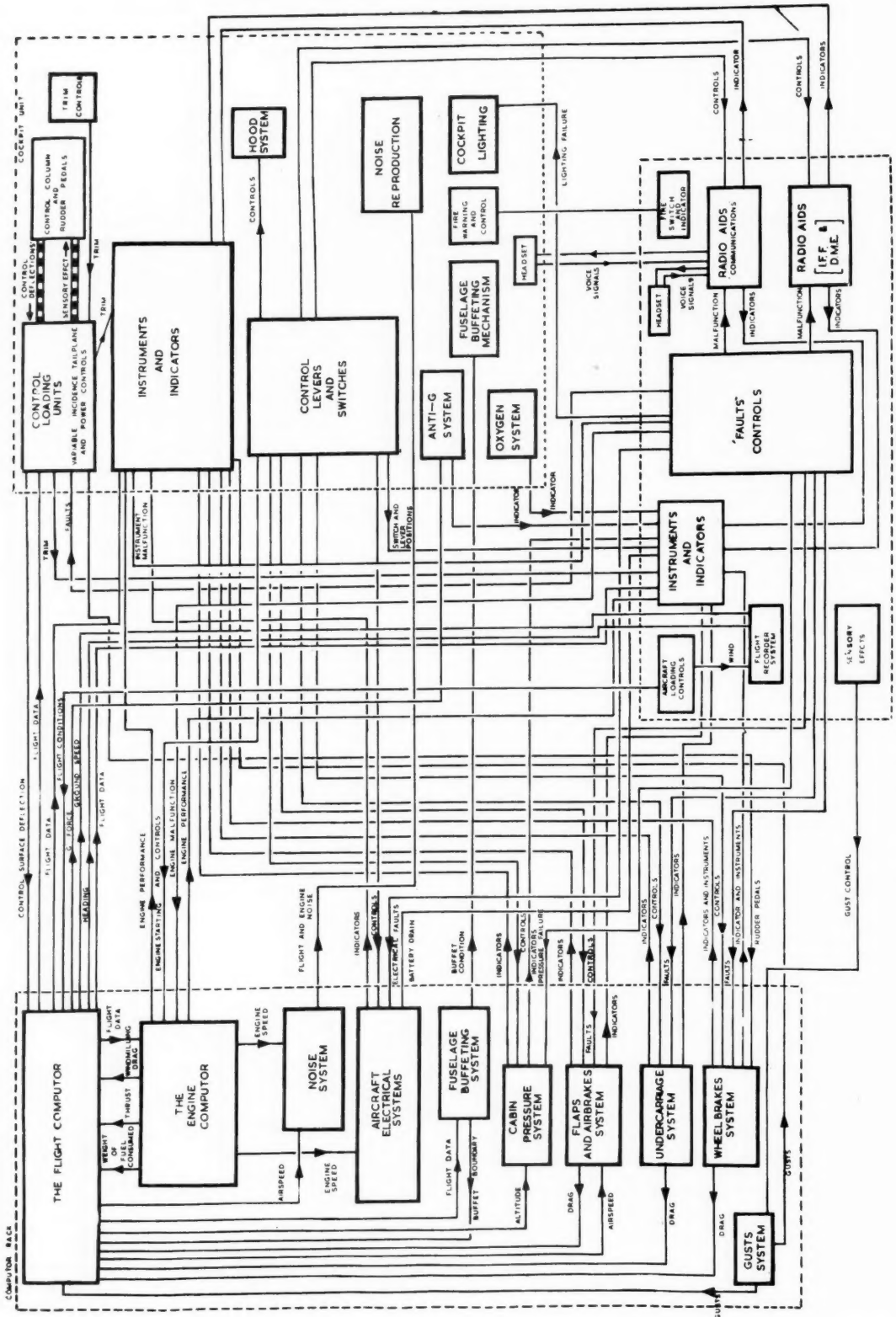


FIGURE 2. Information routes in a modern military simulator.

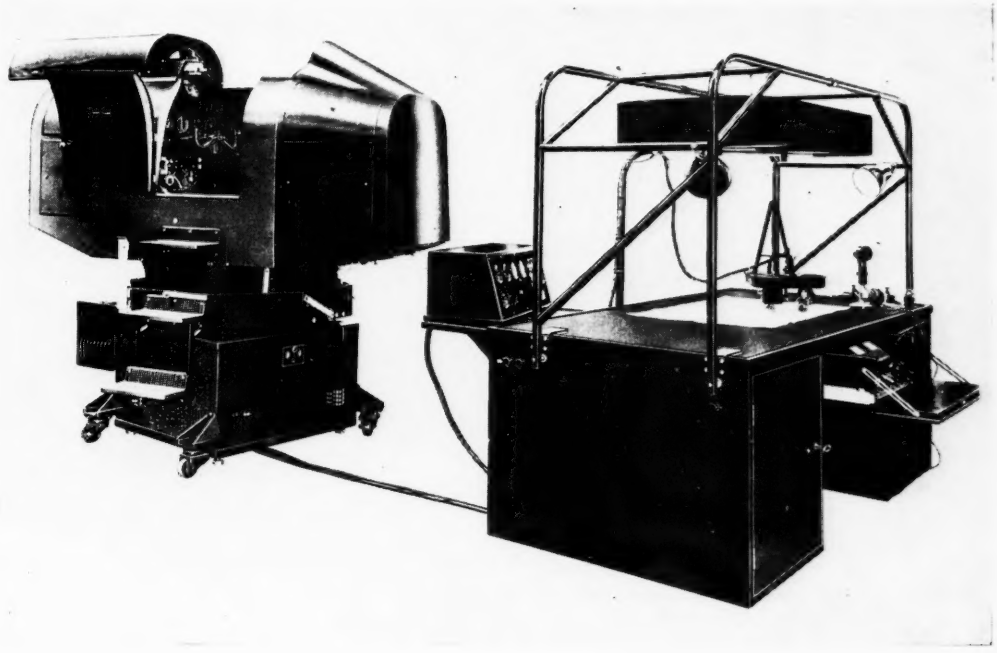


FIGURE 3. Link trainer type D.4.

'*A*', and the changes due to modification of pitch attitude are effected by the control linkage '*B*'. The combined action results in a given position for the valve '*C*'. A spring-loaded cord transfers the bellows motion to a teletorque transmitter '*E*' which positions the air speed indicator '*F*'. Additional realism is achieved by providing vacuum lines to valves controlled by '*G*' the wing flaps, '*H*' the undercarriage and '*J*' the rough air unit, the latter introducing random disturbances when put into operation by the instructor.

This empirical approach to the flight computer may still be entirely adequate in meeting the demands of procedure trainers in an economical and sufficiently realistic manner and many of the radar and navigational trainers used during the war[5] incorporated these principles to provide the translational data. Fig. 5 illustrates a modern twin-seat multi-engined trainer using the basic Link features with a comprehensive eight-station radio aids unit and Cartesian recorder. The cockpit of this trainer which is shown in Fig. 6, has a conventional dual control and an instrument presentation which can be varied to suit individual training requirements. Motion in pitch and bank control loading are both provided by the vacuum bellows system and provision is made for realistic cockpit lighting and noise effects. The equipment has been found to fulfil an important requirement for an inexpensive, easily maintained and compact radio and navigation procedure trainer which will be within the means of the smaller airline operator, or, alternativley, could be used on a large scale by Government agencies or the Services.

4. The Day Landing Trainer

A major improvement in the characteristics of pilot training devices arose from their motivation by devices which automatically computed the attitude of the aircraft to the air flow past it and thence the forces and moments involved—in brief, by the analogue flight computer as distinct from the more empirical mechanisms previously employed.

This proposal appears first to have been made by Hellings in 1942[6] and was embodied in a device known as the Day Landing Trainer constructed at that time under the direction of the Ministry of Aircraft Production. Its general nature is shown in Fig. 7 which is extracted from an Empire Central Flying School research flight report[7], and reproduced here by kind permission of the Ministry of Supply.

The purpose of this device was the training of pupils at the elementary tuition stage in the art of judging the round-out, hold-off and touch-down, including recovery

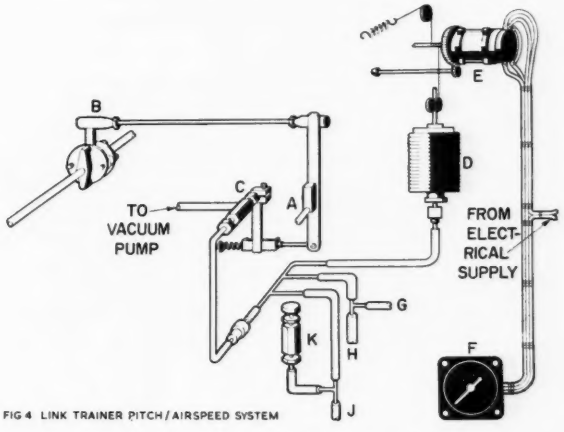


FIGURE 4. Link trainer pitch/air speed system.

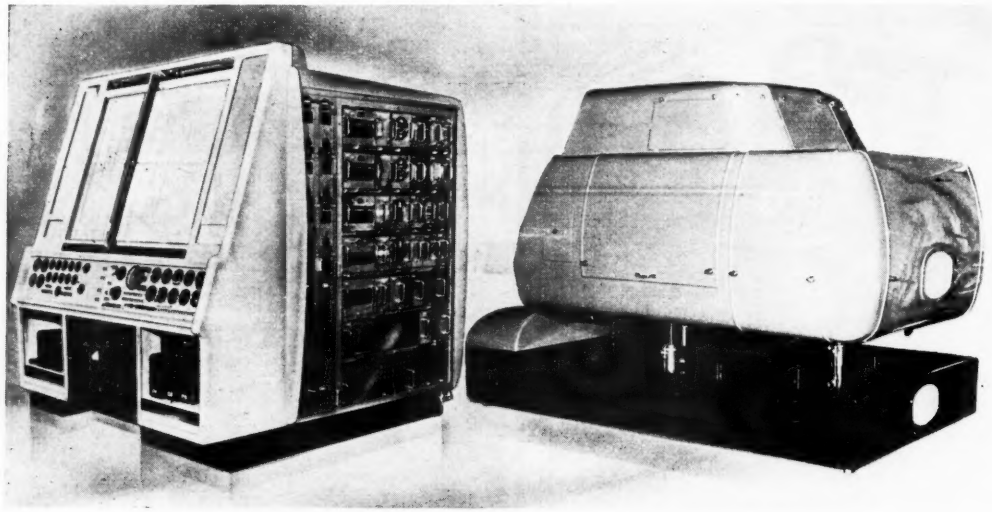


FIGURE 5. A 100/500 general purpose trainer.

with the use of engine in case of a bounce. For this purpose, the fuselage '*A*' was suspended to pitch about an axis passing through the pupil's head, and he applied his eyes to a binocular periscopic sight '*B*' of a cranked construction such that its entrance pupil was outboard of the fuselage, but also on the pitch axis and looking forward. The sight contained a stereo pair of silhouettes of the aircraft's supposed windscreen structure and beyond this were arrangements which, in effect, put the user's eyes, greatly stopped down, at one-hundredth of their normal distance apart at the sight entrance. From here he viewed a 1/100th scale model of an airfield constructed as an endless band '*C*' automatically raised and lowered in accordance with computed height and running at the computed forward speed.

The purpose of this trainer involved flight over a wide range of pitch attitudes without corresponding

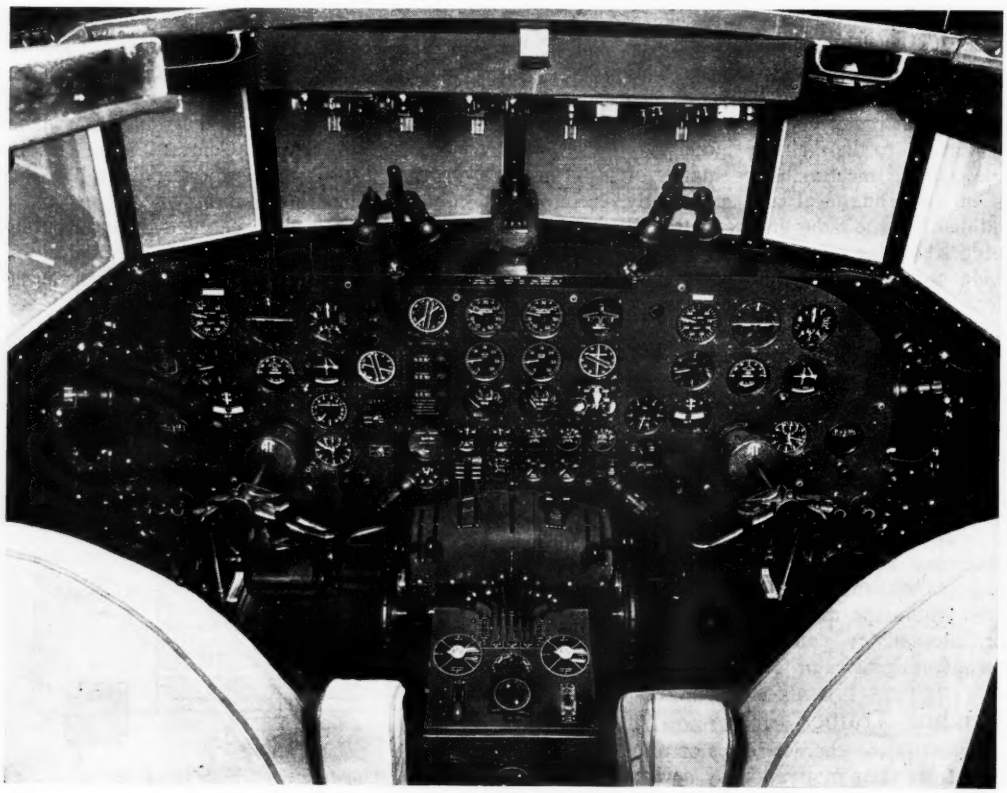
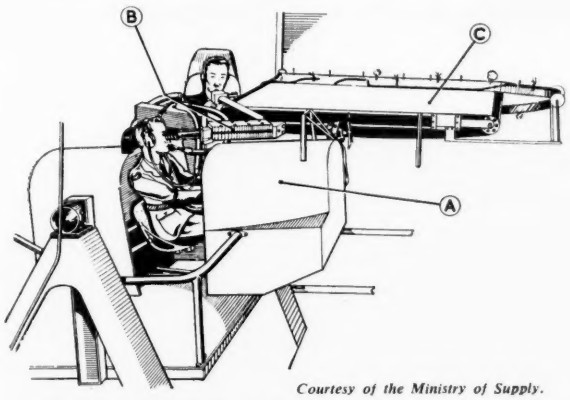


FIGURE 6. Instrument panel installation.



Courtesy of the Ministry of Supply.

FIGURE 7. E.C.F.S. daytime landing trainer general view.

steepness of flight path, (especially during the hold-off period) and it was also envisaged that the device should be capable of ready conversion from one nominated aircraft type to another as regards its handling characteristics. The empirical type of flight mechanism did not offer these facilities, and consideration of the problem led to use of an analogue computer solving the simultaneous differential equations for flight path and air speed in the pitching plane in terms of angle of attack.

The system was basically mechanical and embodied multiplying and integrating elements, the principles of which are still in use.

5. Mechanical Analogue Computing Elements and their Application in Modern Flying Trainers

In analogue computers, the vital elements are those which carry out functions of multiplication together of two independent variables and the integration of a variable with respect to time. The constructions used in the mechanical system for these two purposes are shown in Figs. 8 and 9.

The multiplying mechanism of Fig. 8 consists essentially of three pulleys, one of which is movable, mounted in a frame in such a way as to form a bight in a run of steel tape (1) passing over the pulleys. The movable pulley (2) which actually forms the bight is carried by a block (3) mounted so as to slide vertically in the frame (4), the frame itself being arranged to slide horizontally. Behind the block is a lever (5) pivoted at one end so as to form a ramp of adjustable slope against which bears a small roller follower (not visible) mounted coaxially with the movable pulley (2), pressure being maintained by the tension in the tape.

One of the independent variables, represented by a mechanical movement, adjusts the pulley frame horizontally to varying distances from the ramp pivot; the other input variable adjusts a bar (6) which raises the free end of the ramp to varying distances above the horizontal. Consideration will show that the vertical displacement of the block carrying the movable pulley, and consequently the length of the bight formed in the tape by this pulley, depends simultaneously on both these input displacements and consequently upon their product.

Any point in the tape outgoing from this device will therefore move in accordance with changes in the product of the two variables. The tape may be passed through other devices to facilitate the addition of further terms figuring in the relevant equation.

Where in the flight computer system a particular variable figures in several multiplications (an example being dynamic pressure) the devices handling these multiplications may be superposed and the pulley frames coupled together for common movement in accordance with this variable.

It will also be appreciated that this mechanism may be applied for purposes of division of one variable by another; in this event the numerator variable is inserted by pulling externally on the tape so as to control the length of the bight, and the denominator quantity is

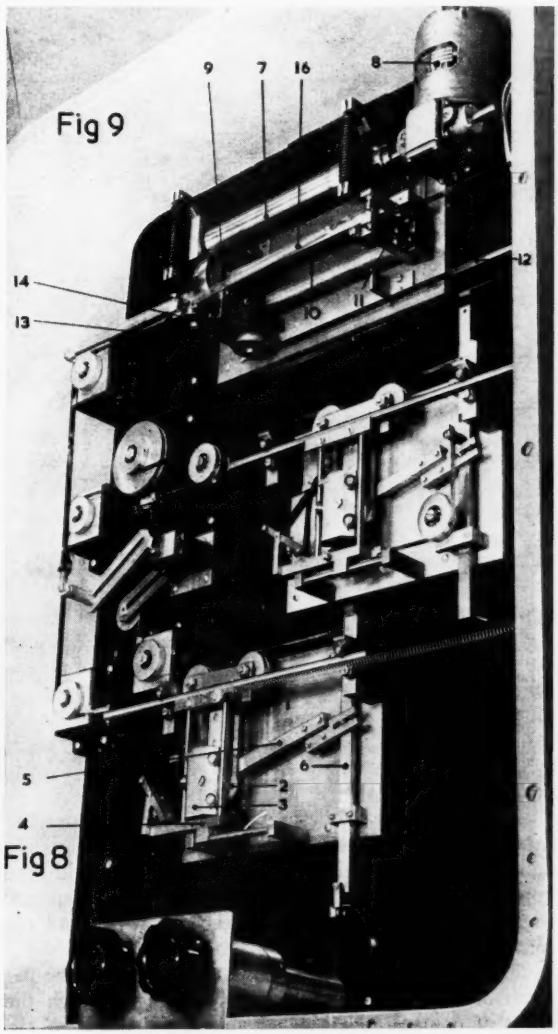


FIGURE 8 (*bottom*). Mechanical multiplying mechanism.
FIGURE 9 (*top*). Mechanical integrator.

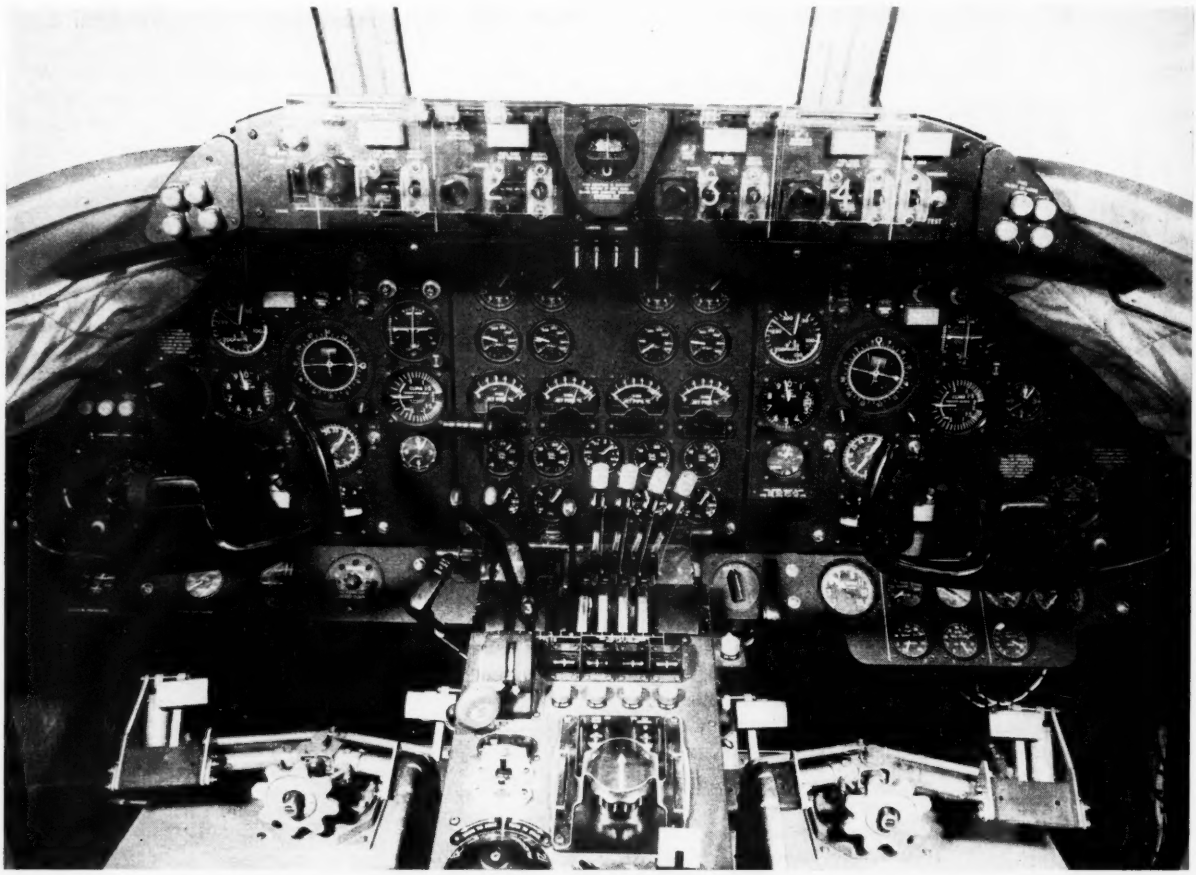


FIGURE 10. Cockpit of Viscount " 744 " Type trainer.

used to move the pulley frame horizontally; thus the linkage operates to regulate the slope of the ramp and the setting of the vertical sliding bar provides the desired quotient. In this use, the device has, of course, the traditional limitation when the denominator approaches zero, *i.e.* when the follower behind the movable pulley approaches the pivot of the ramp.

The mechanism for integration with respect to time is illustrated in Fig. 9. It consists of a hardened steel roller (7), rotated at a constant speed by a synchronous motor (8) and driving a follower wheel (9) constructed from a large diameter ball bearing with its outer cylindrical face crowned and hardened so as to provide point contact with the roller. This wheel is carried by a bar (10) disposed parallel to the roller axis and capable of movement in this direction; this bar being mounted in a swinging frame (11) so that with the application of spring tension to the latter, the requisite degree of contact pressure between the roller and the follower may be maintained.

The follower wheel is so mounted in its carrying bar as to be steerable about an axis passing through the point of contact and it will be appreciated that if the wheel is turned so that its axis of rotation makes an angle with that of the roller it will travel along, carrying its mounting bar with it, at a speed proportional to the tangent of that angle, so that the longitudinal position of its mounting bar (10) at any time represents the time integral of the steering displacement applied.

The latter displacement is accordingly the quantity to be integrated and is applied by passing an input tape (12) around two pulleys (13), (14), carried on the steering head (15) of the arrangement. The head is urged towards full lock in one direction by a spring (16), and externally applied changes of the effective length of the tape, in accordance with the integrand quantity, accordingly determine the steering angle. The construction of the device, with its virtual point contact, imposes very little frictional torque against accurate setting of the steering angle, and the spring tension arrangement has the advantage of ensuring that the device exhibits virtually no lost motion in operation.

It is of interest to note that if the tape run is terminated at the steering head, travel of the arrangement will itself modify its own steering angle, so that the device becomes a positional servo instead of the pure integrator. The output tape is connected to the slider bar, the device thus providing power amplification.

Mechanical analogue computers using these techniques have been found to have a performance, with

FIGURE 11. Computer room, B.E.A. Elizabethan and Viscount 701 flight simulators.

regard to threshold sensitivity at least, comparable with their electronic equivalent. In many applications they may also appeal because of ready understanding of their method of operation and their ease of maintenance. For these reasons they have been incorporated in the "Type" trainers produced by Air Trainers Link Ltd.

This "Type" trainer, intermediate in cost and complexity between the basic procedure trainer and the full flight simulator, emulates the appearance and behaviour of a nominated aircraft type to an extent which will still guarantee useful air crew conversion training. Fig. 10 shows the cockpit layout

of a Viscount 744 Type trainer as supplied to Capital Airlines.

Economy in cost is effected in three major ways:—

(*a*) By relaxing the requirement that such items as seats, controls and other internal cockpit features must correspond exactly to those of the aircraft, while retaining functional correspondence in such matters as length of travel, sense of operation and relative disposition.

(*b*) Omission or simplification of certain of the auxiliary systems by agreement with the user. A common example is the auto-pilot system, dummy controls being fitted to preserve layout realism.

(*c*) The use of simplified systems for flight and power plant analogue computers; these give accurate results only in a limited number of selected flight conditions and power settings.

The computer equipment, based on the mechanical principles described above, is usually mounted on a large free-standing vertical panel to the side of the trainer fuselage, the flight and auxiliary systems being on one side and the engines on the other. Flexible stainless steel tapes of 0·002 in. thickness are used to transmit movements in the mechanical analogue and the arrangement is such that any tape is maintained under tension from a spring fitted at the free end, thus taking up any lost motion in the various mechanisms which operate on it. These mechanisms can therefore be constructed with relatively easy manufacturing tolerances and at moderate cost without suffering the usual limitation of conventional push and pull linkages.

It has been found possible to mount the fuselages of these Type trainers to allow for controlled displacement about the pitch and bank axes. The fuselage chassis is mounted on a universal joint situated well aft so that pitch displacements have a vertical component at the pilots' seats which adds to realism, especially when random displacements are applied by mechanisms simulating atmospheric turbulence during flight. The displacements are effected by hydraulic rams controlled mechanically by tapes running from the computer assembly; since the flight computer is a genuine analogue the system allows for the application of different types of control signal, or mixtures of them, for this purpose.

6. The Electronic Computer

Although the principle of using analogue flight computers in flying trainers dates from 1942 the extensive, high fidelity systems required by the modern flight simulator became feasible only with the aid of electronic techniques and components developed well after that time—notably the feedback amplifier and small motor-generator units capable of being driven by such an amplifier and of quickly setting potentiometers and data-transmitting elements. Fig. 11 is a general view of the room in British European Airways' simulator building housing the computer equipment for their Elizabethan and Viscount 701 flight simulators.

In electronic analogue computers the medium used for representation and transmission of information is usually a direct or alternating voltage whose value and polarity or phase respectively correspond to the magnitude and sense of a force, moment, velocity or displacement in the system being simulated. Such electrical signals can readily be added, scaled up or down, resolved or compounded and ultimately used to operate remote electrical instruments or actuators.

Of all the systems involved in flight simulators, the computer handling the six equations of motion of the aircraft is the most exacting in its demands on equipment and the one most affected by any shortcomings in the behaviour of the components of which the systems are composed. Such a flight computer, shown schematically in Fig. 12, embodies a large number of closed and inter-connected loops. Forces and moments are integrated with respect to time to give corresponding linear and angular velocities and these, in turn, to provide linear and angular displacements. The displacements so obtained are utilised in the computation of aerodynamic and gravitational forces and moments. These terms are then returned to the system at various appropriate points, including the input, where they act as stabilising factors and complete numerous self-balancing loops.

In a stable aeroplane, when input moments are altered or added to, either by the pilot or as a result of external disturbances, the system moves quickly and in a highly damped manner into a condition in which moments are once more balanced. This normally produces an unbalance in the linear aerodynamic forces and the system then seeks a new combination of air speed, rate of climb, etc., at which these forces in turn balance. In the pitch loop, for instance, this condition is approached in an oscillatory manner (phugoid) the motion being lightly damped and having a long time period.

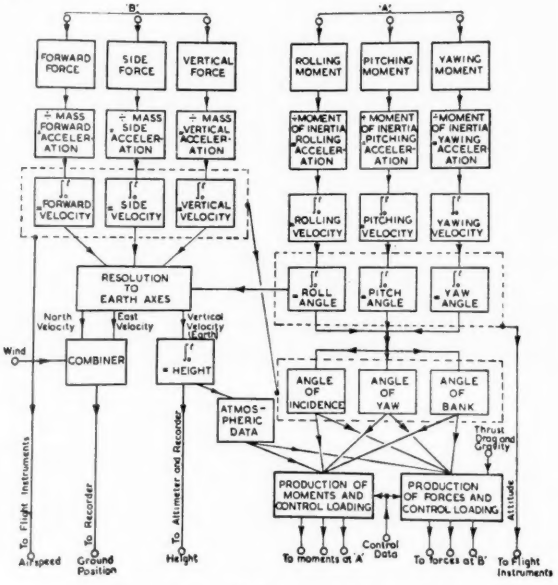


FIGURE 12. Flight computer schematic.

In order to preserve realism in the handling of the simulator, it is of the utmost importance that the flight computer should not suffer appreciably from defects which may be colloquially described as sponginess, lost motion or stiction. Otherwise, small movements of the controls will not produce the expected response, or time-lags will occur, giving rise to over-control or over-correction, and the training value of the device will largely be lost.

Assuming that the potentiometers in the computer system have a sufficient number of turns for their electrical outputs to be substantially progressive, the main sources of such dynamic error are usually to be found in the servo units present. Much ingenuity has been expended on minimising these effects; three examples of methods by which satisfactory results have been achieved are worthy of mention.

6.1. INTEGRATION IN ELECTRONIC ANALOGUE COMPUTERS

The traditional method used in flight computers of integrating a signal voltage with respect to time is that first suggested by F. C. Williams[8]. In this, a motor is driven from a high gain amplifier whose input is the difference between the signal voltage to be integrated and a voltage proportional to motor speed derived from a tacho-generator driven by the motor. In the steady state the motor will run at the speed for which the net input signal is approximately zero, *i.e.* at a speed proportional to the signal to be integrated, so that a potentiometer driven by the motor and excited with a steady voltage supply will deliver from its slider a voltage proportional to the time integral. Either a.c. or d.c. motor-generators can be used for this purpose depending upon the nature of the signal voltage. In both cases, however, these motor generators will have mass requiring to be accelerated, perhaps from rest, and threshold friction may prevent them from responding at all to signal changes below a certain level.

In a.c. computers, the servo inertias can be reduced and response improved to provide time constants within a few milliseconds by raising the loop gains and the carrier frequency of the signal voltages. This, however, will enhance the risk of introducing spurious induced voltages in the complex wiring of the computers. These quadrature components, although too small to affect the accuracy of computation appreciably, may give rise to overloading in the input stages of amplifier circuits. Special steps must be taken to avoid this by careful screening and the use of compensating circuits.

With d.c. computers, however, an alternative method of integrating with respect to time is possible in the form of the Miller integrator. This consists basically of a high gain d.c. amplifier with a condenser in the feedback circuit. A steady direct voltage applied to the input results in an output voltage which changes with time at a rate proportional to the magnitude of the input voltage, so that at any instant the output voltage represents the time integral of the input signal. Such a device, in which there are no moving parts, is not subject to the disadvantage of the servo motor, and its adoption has brought about a completely new standard of sensitivity and stability in the flight computers

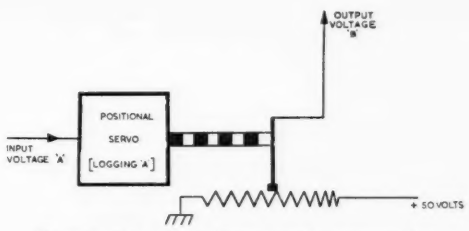


FIGURE 13(*a*). Non-linear function generation.

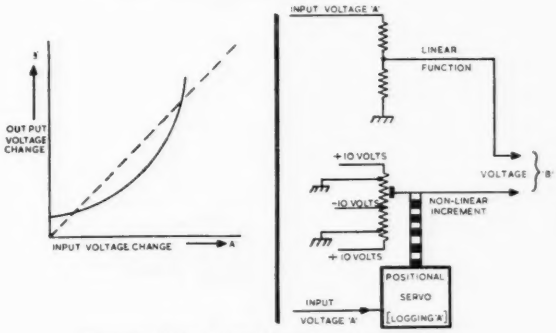


FIGURE 13(*b*). Non-linear function generator.

produced by Air Trainers, and latterly by its associate concern Link Aviation, in the United States. Circuit refinements and means for detecting and correcting drift in the d.c. amplifiers have eliminated the majority of disadvantages previously attributed to the use of d.c. signals.

6.2. GENERATION OF NON-LINEAR FUNCTION OF A VARIABLE

The generation of a signal which is some specified non-linear function of a variable input signal can be performed without involving mechanical mass and friction by diode networks and, in analogue computers designed as mathematical tools for research purposes, use is sometimes made of these devices. For various practical reasons, however, the servo-driven potentiometer is still preferred in computers for air crew training devices.

Figure 13(*a*) shows diagrammatically the conventional method of obtaining a voltage '*B*' which is a non-linear function of voltage '*A*'. A positional servo unit is employed to displace the slider of a potentiometer by an amount proportional to voltage '*A*'; the servo motor is driven by a suitable amplifier whose input voltage is the difference between voltage '*A*' and the output of a linear feedback potentiometer, not shown, also driven by the servo. (It is usually said to be "logging" *A*).

The potentiometer shown has a fixed voltage across its winding, and the latter is so contoured, or alternatively electrically "shaped" by auxiliary loading resistors connected to it, as to yield the specified function of *A*. With this arrangement any lag, overshoot or threshold insensitivity of the servo/potentiometer unit will, as already explained, adversely affect the sensitivity or stability, or both, of the computer of which it forms part.

A method of minimising this is illustrated by Fig. 13(*b*) which shows as a full line a typical non-linear function B of an input variable A. The dotted line is a linear function of A so chosen as to approximate to function B as nearly as possible. A voltage representing this linear function is obtained directly from voltage A, if necessary through a fixed potential divider for scaling purposes, and the servo/potentiometer combination is used only for providing the increment of voltage required to convert it to the specified non-linear function; both voltages being subsequently added together by means of a summing amplifier (not illustrated) to produce the final voltage 'B'.

With this arrangement a change in the input voltage will cause an instantaneous change of the output voltage from the amplifier by approximately the correct amount; any lag due to the servo unit will appear only in the correction of this to the exact value, and is accordingly of less consequence. An incidental advantage of this arrangement is that for a given number of turns of wire on the servo/potentiometer the steps in the output voltage are greatly reduced in effective magnitude.

An alternative method of "by-passing" the servo dynamically is for the potentiometer to be energised, not by a fixed voltage but by the linear voltage for 'A'; in this case the potentiometer is contoured in accordance with that non-linear function of A which must be used as a factor to obtain the specified result.

6.3. GENERATION OF THE PRODUCT OF TWO INDEPENDENT VARIABLES

Figure 14(*a*) illustrates the conventional method of computing a voltage which represents the product of two independently variable voltages A and B. One of these input voltages (A) is applied through a positional servo assembly to positioning the slider of a potentiometer according to A, while the winding of this potentiometer is energised by the other variable voltage B. Consequently the output voltage delivered by the slider depends both on the slider position 'A' and the energising voltage 'B', and is therefore proportional to their product AB.

A means of minimising the effect of servo lag in this operation, applicable only where d.c. computation is used, makes use of the following expression for the product of A and B

$$AB = \int (A\dot{B} + B\dot{A})\ .dt$$

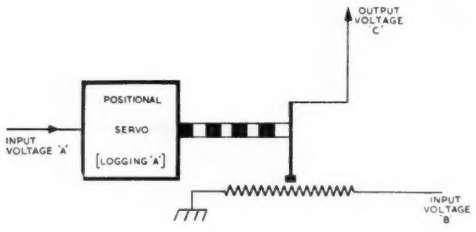


FIGURE 14(*a*). Multiplication of two variables.

Two servo/potentiometer units are employed as illustrated by Fig. 14(*b*). One is controlled by the variable voltage 'A' to position its potentiometer in accordance with that quantity, while the winding of this potentiometer is excited by a voltage representing the rate of change $\dot{B}$ of the other variable, so that the slider of this potentiometer gives a voltage representing $A\dot{B}$. The other servo/potentiometer unit is used in the converse fashion to compute a voltage representing $B\dot{A}$. These two output voltages are then summed at the input of an electronic integrator, so that the output of the latter is the time integral of this sum, that is, the voltage for AB in accordance with the equation stated.

It will be seen that with this arrangement any change of A or B will appear not only as an impulse to the appropriate servo, but instantaneously as a change of exciting voltage across the other's potentiometer, so that there will be an instantaneous change of the relevant partial product term, and of the amplifier output, which does not include the servo response time. If the servo response were unduly delayed, the product voltage, during such delay, would change at a progressively incorrect rate; but this is of second order importance in determining the transient behaviour.

It would appear at first sight that this technique involves undue complication of input signals and equipment compared with the conventional method, but this is in fact more apparent than real. In a flight computer, with its successive stages of integration and with its eventual positional outputs serving as acceleration terms for input use as required, voltages representing the rates of change of significant quantities will, in general, already be present and available as well as the signals for the quantities themselves. It is likewise true that in such computers in general, there will be a need for both quantities A and B to be logged by servos for positioning data-transmitting devices to control cockpit instruments, and so on, which are external to the dynamic loop in which the multiplication operation is required.

The net effect of full use of these techniques in flight computers using d.c. systems can perhaps be summarised by saying that if the computer is disturbed, for example in pitch, by a small elevator movement, the initial quick damped oscillation to a new combination of variables giving a fresh balance of moments could occur without requiring any mechanical servo movement at all. The flight computer servos, in fact, are present

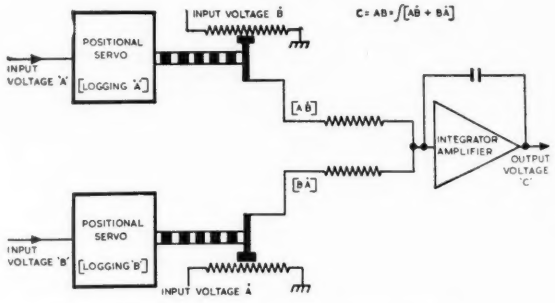


FIGURE 14(*b*). Multiplication of two variables.

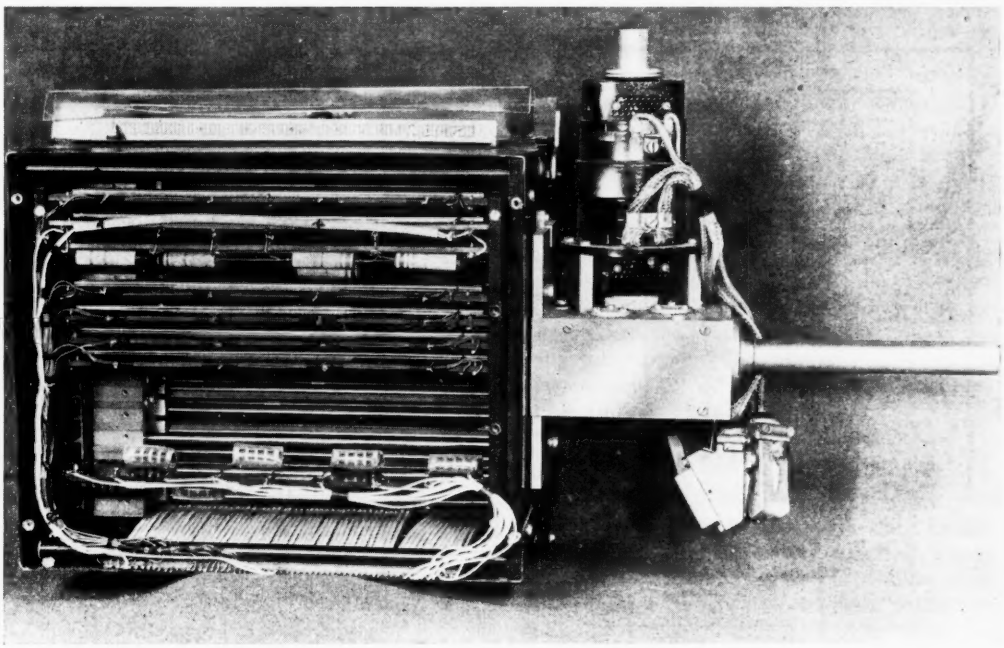


FIGURE 15. Standard electronic servo-unit assembly.

only to provide specified departures from linearity, to log relatively slowly varying quantities, such as air speed, altitude and heading, and to operate cockpit instruments and other effects external to the dynamic computing loops.

6.4. STRIP-CARD SERVO UNITS

The performance and compactness of electronic analogue computer systems used by Air Trainers has been greatly aided by the development and use of the type of servo/potentiometer assembly illustrated in Fig. 15. This differs greatly from more conventional arrangements in which the servo motor drives a bank, or banks, of mechanically coupled rotary potentiometers. Each potentiometer is wound on a straight card 8 in. long and 2 in. deep and carries a conducting strip or busbar running close alongside its working edge. These cards are held in closely spaced relationship by sliding their ends into slots milled in the ends of a rectangular box, and the moving contact assembly consists of a member shaped like a broom having its handle pushed into and out of the box by the externally mounted motor and its head lying across the card edges. This head is of insulating material and has, for each card position, a spring contact which transfers the picked-off voltage to the busbar strip on the card, so that all electrical connections can be made to fixed tags at the card ends. The slots at one end of the box contain light arched springs, and at the other end set screws by which cards can be given individual endwise adjustment in zero setting.

Among the advantages obtained by this method of construction are:—

(*a*) Compactness; for example up to 15 potentiometers can be accommodated in a box 11 in. × 9 in. × 5 in. deep and if the depth is increased to 8 in. a second stack of potentiometer cards can be placed behind the contact bridge, making up to 30 in all.

(*b*) Any potentiometer can be readily adjusted, removed or replaced without disturbing others.

(*c*) All potentiometers are equally directly driven, none being subject to the cumulative error and backlash which can be present in ganged assemblies.

The example shown in the figure is a 30-card unit having some of the cards in the top layer removed to show the contact bridge (at the left-hand end) and the

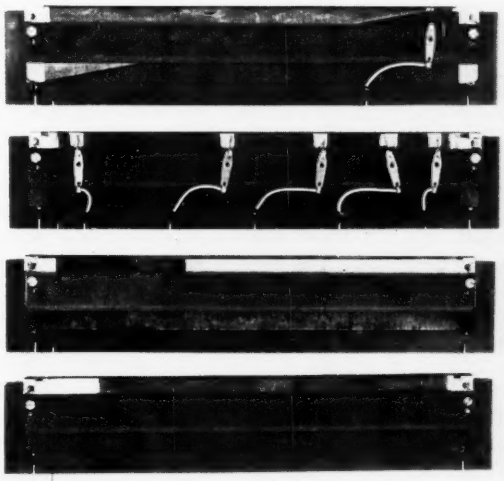


FIGURE 15(*b*). Strip card potentiometers.

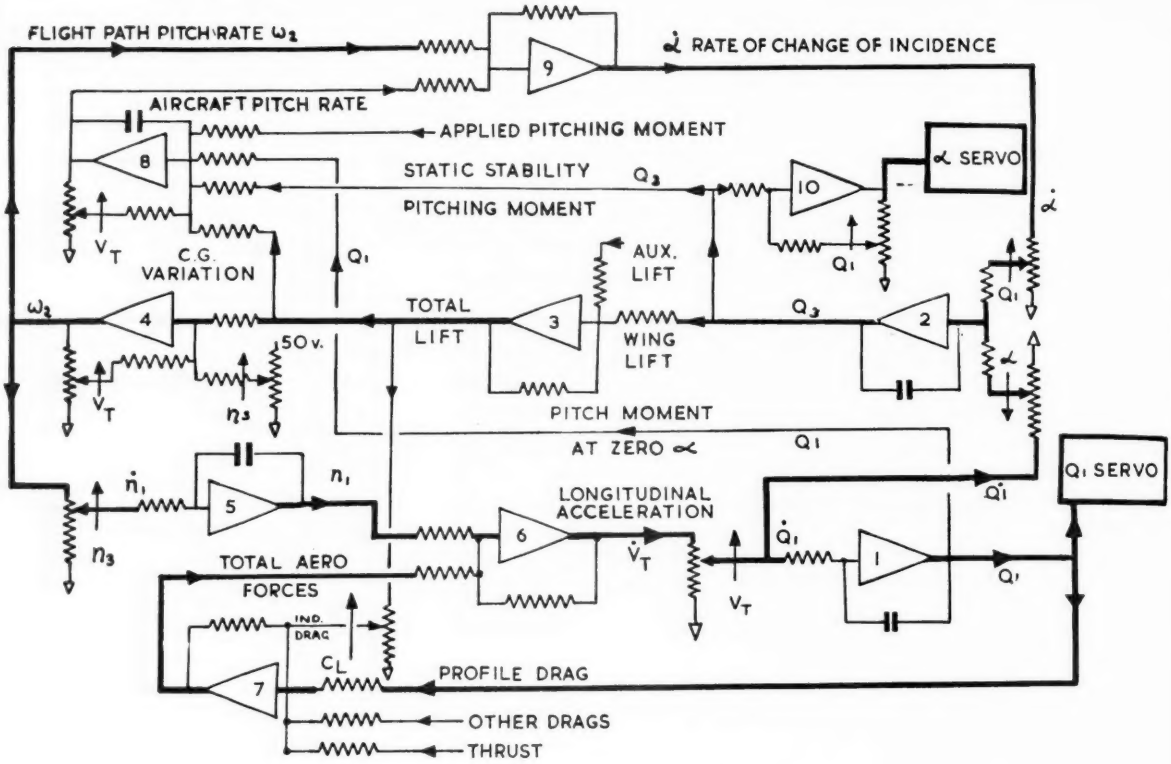


FIGURE 16. Electronic pitch air speed loop.

working edges (winding and busbar) of some of the potentiometer cards in the inner stack. The rear face of the box, of course, is also removable to allow access to these. The tubular extension on the right-hand side is a protective cover for the handle carrying the contact bridge when the latter moves towards the right-hand end of the box. This handle is a simple steel rod frictionally driven by the motor; in cases where rotary data transmitting devices, such as teletorques, are externally mounted for positioning by the motor, and must remain in synchronism with the bridge, the handle of the latter is formed into a rack having a pinion engagement with the motor drive.

6.5. APPLICATION TO THE ELECTRONIC PITCH/AIR SPEED SYSTEM

Figure 16 gives an example of the pitch/air speed section of a d.c. flight computer system using the techniques described. For ease of study, all features have been omitted which are not strictly necessary in considering its dynamic behaviour; only the principal forces and moments are dealt with, and details have been omitted of arrangements for introducing the effects of air density changes and generating correct stalling behaviour. Electrically, the circuits have been simply drawn and amplifiers have been left out where their function is only to change the sign of a signal voltage. An arrow denoting slider movement in a potentiometer has a symbol specifying the servo which moves it, the servo itself being shown separately in the diagram as a simple labelled box.

The computer uses the "wind axes" system as the reference frame for forces and moments and their effects, that is to say an orthogonal right-handed system having one axis parallel to the instantaneous flight path, a second at right angles to it spanwise, and the third perpendicular to both in the aircraft's plane of symmetry; however, its principles are equally applicable to computers based on "body axes" fixed in the aircraft's structure. The attitude of the axis system to the vertical from earth is defined by the cosines n_1, n_2, n_3 of the angles between this vertical and the three axes respectively, so that the gravity component forces are linear functions of these quantities, but the diagram deals, for simplicity, only with the two involved in pitching with wings level, *i.e.* n_1 and n_3. ω_2 is the angular rate of pitch of the axis system.

The two fundamental variables in the computer are d.c. voltages Q_1 and Q_3, representing aerodynamic forces corresponding to the components of dynamic pressure along the two axes. Q_3 is wing lift corresponding to angle of attack (α), which is defined in the computer by the relation

$$(\alpha)=\frac{Q_3}{Q_1}$$

Consideration of the system may conveniently start at the right-hand side, where potentiometers in (α) and (Q_1) servos are respectively energised by voltages for

($\dot{Q}_1$) and ($\dot{\alpha}$) and their outputs summed and integrated by amplifier No. 2 to give wing lift Q_3 by the multiplication technique previously explained. Auxiliary lifts (for example from flaps) are added by amplifier No. 3, and the gravity component (n_3) added at the input of amplifier No. 4. In this case, the usual feedback voltage is multiplied by true speed V_T. Since the action of a high gain feedback amplifier is to generate an output voltage which brings its net input to zero, consideration will show that this arrangement will produce an output voltage representing net upward or downward force divided by V_T, which is (ω_2), the rate of pitch of the flight path.

At amplifier No. 8 the pitch rate of the aircraft itself is computed by summing and integrating the pitching moments, and is algebraically added to (ω_2) at amplifier No. 9 to give ($\dot{\alpha}$) for use at the input end, thus closing the loop in which the short-period motion of the aircraft is simulated.

The (α) servo is positioned by amplifier No. 10, which divides Q_3 by Q_1 using the technique described in connection with amplifier No. 4.

The lower loop computes the forces along the flight path and hence ($\dot{Q}_1$). The gravity force (n_1) is obtained by amplifier No. 5 integrating its rate of change ($\omega_2\eta_3$), and this is added by amplifier No. 6 to the sum of the aerodynamic forces involved from amplifier No. 7. The nature of these is evident from the diagram; the C_L servo (not shown) required for computing the induced drag term is positioned by an amplifier which divides total aerodynamic lift by (Q_1).

Amplifier No. 7 accordingly gives an output representing true acceleration ($\dot{V}_T$) along the flight path. This is applied in two ways:—

(*a*) To operate a conventional integrating servo arrangement (not shown) which logs V_T for the various division operations already mentioned.

(*b*) To obtain, by the special multiplying technique, a voltage for $(\dot{Q}_1)=2V_T\dot{V}_T$, which in turn is used in the (Q_3) computation as earlier described, and is also integrated to (Q_1) by amplifier No. 1 and logged by the servo shown.

The combination of techniques described in this computer has the result that, on a change of applied pitching moment, the short period motion to re-balance the moments, and the consequent immediate change in lift force, both occur without any limitation in sensitivity or response from mechanical servo imperfections. The subsequent balancing of forces along the flight path does depend upon the action of servos present, in particular that logging (Q_1), but this phugoid motion is a long period one and no difficulty is experienced in securing adequate inherent stability.

It is worth remarking that the system is such that the effect of drift in any of the amplifiers is to cause a change in trim of the simulator which, in practice, is substantially negligible. As an example, if the (Q_3) output from amplifier No. 2 should increase, this will generate increases in (ω_2) and induced drag with a consequent change in ($\dot{Q}_1$) until the input to amplifier No. 2 has fallen sufficiently to check the drift. The simulator therefore, will now, with the controls untouched, be climbing a shade more steeply at a slightly reduced air speed. Such a change will occur very slowly, and the stability of modern d.c. amplifiers is such that in practice such variations as may occur between routine checks do not take the simulator outside the "fleet spread" of the aircraft type being simulated. Means are available for automatically detecting and correcting drift in any individual amplifier which may have a particularly critical duty, but recourse to this is very much the exception; for example, in the complete flight and power plant computer systems of a Viscount flight simulator only 15 out of 120 amplifiers have embodied this provision.

7. Sensory Effects

In many respects flight simulators now in service include realistic sensory effects as an important feature of air crew environment, particularly those associated with noise, buffet and vibration, and simulation by what are known as control loading devices of the forces felt through the pilot's hand and foot controls is of course essential even in the most unsophisticated trainers. Problems in this field still remain, however. Control loading mechanisms are under continuous development to meet increasingly severe technical requirements; and adequate suggestion of physical accelerations, and the convincing presentation of the scene external to the aircraft, are still largely in the experimental stage. It may be of interest to summarise developments under each of these three headings.

7.1. CONTROL LOADING

An essential feature of any device simulating the behaviour of an aircraft is the provision of some type of spring mechanism (of a resilient nature) which simulates the aerodynamic hinge moments felt by the pilot's hands and feet when the flight controls are displaced from their trimmed positions. Improved control loading mechanisms accordingly share the increasing refinement of the computers and other aspects of the training devices in which they are embodied. In the early basic trainers they were simple mechanical springs; later came requirements for varying the datum by trim control and for automatically varying the effective stiffness or rate of the spring in accordance with the computed indicated air speed or dynamic pressure at each instant.

These additional requirements may involve adjustments to the mechanism while the spring attachment is stressed. Because it would not be permissible for the stress to be felt by the pilot as an anomalous load on the trim wheel, or for it to load the computer system abnormally, the requirement arose for servo adjustment of the control loading forces.

Various types of synthetic spring have been developed for this purpose, for example suction bellows, compressed air rams, and electrical torque motors, whose load/displacement laws and no-load settings

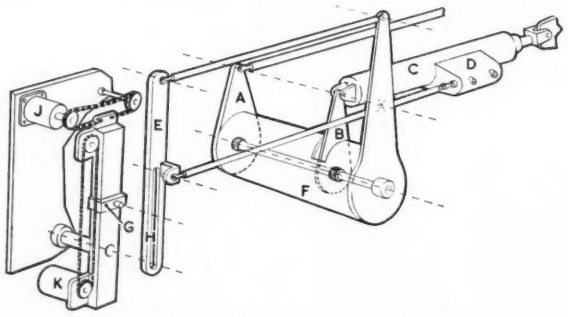


FIGURE 17. Torsion bar control loading unit.

could be controlled by such means as pneumatic valves, rheostats or amplifiers. Such forms of control loading are still in satisfactory use on the procedure and "Type" trainers previously described and, indeed, on many of the flight simulators so far constructed.

With the demand for increasing refinement in flight simulators it has become increasingly desirable for the pilot to feel the rapid and transient changes in trim which occur due to the variations in the effective angle of attack of a control surface during an applied manoeuvre, or whenever a short period motion of the aircraft is induced. Furthermore, the increasing use of power assistance and power operation of flying control surfaces, and the resultant requirement for simulating anomalous effects due to their partial or complete failure, call for the reproduction of exceptionally wide ranges in effective stiffness or rate, and a variety of exaggerated non-linearities in the force/displacement characteristics of flight controls.

Two recent developments in control loading systems have been devised to satisfy these new requirements. One which is currently being incorporated in Air Trainers' flight simulators is illustrated diagrammatically in Fig. 17.

The spring is a mechanical one—normally a simple torsion bar splined at its ends into radius arms *A* and *B*. Its loaded end "*A*" is conventionally connected for displacement by the pilot's hand or foot control, but its other end "*B*" instead of being clamped fixedly in the general frame of the equipment, is grounded through an hydraulic ram, "*C*". The latter is arranged as a positional servo and has its control valve, "*D*", connected by a light linkage, "*E*", and the tube, "*F*", back to the loaded end "*A*" of the torsion bar. With this arrangement, the "fixed" end of the torsion bar is caused to share the movements of the loaded end in a proportion determined by the geometry of this control linkage. By adjusting this geometry the movement ratio, and consequently the effective rate of the spring, can readily be varied.

The control linkage, which has only to operate the hydraulic control valve, is very lightly loaded and can therefore be adjusted rapidly by a light electrical servo "*K*" operated through an electronic amplifier (not shown) by the appropriate signal or signals from the flight computer to move the pivot pin "*G*" up and down in the slot *H*. It will also be realised that the no-load setting of the spring, that is to say, changes of trim, can be effected with equal quickness and ease by bodily displacement of this control linkage as a whole. This is done by the servo "*J*" rocking the frame of the assembly just described.

Further development in this field has been achieved by Link engineers. Here, the appropriate force is applied to the pilot's control linkage by a hydraulic ram, and the equivalent of a strain gauge is incorporated in the linkage to generate an electric signal representing the force so applied at any instant. This is compared in an electronic computing circuit with the required force, having regard to all the external conditions such as dynamic pressure, trim condition, control displacement, and so on. Any error between the two is applied to an electro-hydraulic control valve regulating the admission and exhaust of fluid to and from the ram. This equipment represents the general solution to the problem, in the sense that the force that should be experienced at any instant is wholly computed by electronic equipment which can readily embody all the variables and their non-linear functions which may be involved. The equipment which has to be physically engineered into the flight control assembly of the simulator consists only of the hydraulic ram with its electro-hydraulic control valve, the strain gauge, and a potentiometer or its equivalent for measuring displacement, which is required as one of the input variables to the external computer.

7.2. PHYSICAL ACCELERATIONS

Since any feasible simulation of accelerations will involve accurately controlled and shockless displacements of a fuselage structure which may weigh more than two tons, it is not surprising to find that there has been some reluctance to embark on this. It has indeed been argued in justification that the pilot flying on instruments must ignore "the seat of his pants" and that a trainer which forces him to follow this precept by giving him nothing to feel is therefore a better trainer than one which moves. This virtue created out of necessity has led to much controversy. Experienced pilots find that a fixed base simulator cannot be flown as smoothly and accurately as the actual aircraft until they have practised to the extent of becoming "simulator conditioned." This often leads to a request for the adjustment of damping terms, control forces, and so on, even though this may conflict with stick-free flight measurement data.

Experience even with the limited cockpit movement systems of the general purpose and "Type" trainers, indicates that pilots have a distinct preference for the incorporation of physical movement. It seems fairly clear that it is not possible to ignore the stabilising effect of "*g*" in the overall control loop and that the physical sensations arising from incipient changes in acceleration are useful as early clues both in achieving smooth handling and in the quick recognition of flight abnormalities. Although it is obviously difficult, if not impossible, to simulate sustained "*g*" forces, the extraction of acceleration rates and other terms derived from the flight computer should enable an optimum

attitude system to be devised within the practical limitations of the problem.

7.3. THE EXTERNAL SCENE

Visual presentation of the world seen from the cockpit has a less important bearing on control except under certain circumstances, such as during a visual interception, on take-off, or landing, where it is patently essential. As handling on or near the ground, particularly in bad weather, represents a very critical phase of all flight operations, any possibility of extending the use of the training device to include these manoeuvres is particularly attractive.

Starting with a ciné film taken by "Cinemascope" type equipment from the cockpit of an aircraft making a "perfect" approach it is possible, by the manipulation of asymmetric optics in the projection system, to simulate the changes in perspective of the runway which would obtain in the event of deviations from this path in either the vertical or horizontal plane, such manipulations being controlled by the flight computer. The use of an actual film, which could be in colour, has obvious advantages, although the ability to include accurate detail will be offset to some extent by the distortion in visual texture and of upstanding objects which must occur in the process described. Within certain limits of height and deviation from the original path such distortion, however, may be acceptable. The equipment required in this process would be relatively inexpensive.

If these limitations are to be avoided the picture seen by the pilot must be derived from some device which views a scale model of the landing area, with arrangements for automatically controlling the position and orientation of this model, relative to the viewing point, in accordance with the pilot's handling of the simulator.

The Day Landing Trainer embodies this principle, as also does a system evolved at the Royal Aircraft Establishment by Calvert and his colleagues[9] for research into the relative merits of different patterns of approach and runway lights. In this latter device the moving "model" was the appropriate pattern of light spots projected onto a stationary screen. The apparent direction and travel of the pattern was obtained by applying these motions to the graticule plate in the projector from which the pattern was produced. This device, however, and that of the Day Landing Trainer, involve direct viewing of the model by the pilot applying his eyes to an optical sight and it is considered that this would be undesirable in the full flight simulator. The presence of the sight would detract from realism in the cockpit and the technique of its use would clearly differ greatly from the pilot's normal procedure in flight, particularly during the transition from instruments to visual handling. The introduction of a prismatic attachment permitting a simultaneous view of selected cockpit instruments and the external scene meets the second of these objections to some extent.

The preferred system would be one in which a picture of the model, as seen from the view point of the viewing device, is projected on to a wide screen in front of the cockpit at a reasonable distance from the pilot's eyes. In this "free head" presentation his actions would be unimpeded, and the visual exercise in convergence and focus would be imposed on him in a more correct manner, although anomalous effects due to parallax can occur with lateral head movement unless the picture is inconveniently remote and correspondingly large.

FIGURE 18. Miles car trainer.

One such method of presentation, usefully employed in the Miles car trainer, is the shadowgraph. Fig. 18 illustrates the illusion obtained in this equipment, produced by Air Trainers Ltd. The shadowgraph technique utilises a moving transparent plate, with opaque markings and relief objects, such as trees. The scene is presented in shadow form on a viewing screen before the pupil, by a point source of light stationed continuously at the pupil's supposed position in the scene itself.

For flight training purposes, this technique has severe disadvantages in that the shadow picture of the more distant parts of the airfield surface would be produced by rays from the light source which have to pass through the plate at almost grazing incidence. In these circumstances minute imperfections in the plate produce unacceptable distortion and much light is lost by reflection and absorption due to its length of oblique travel through the material, so that the illumination of these parts of the scene is insufficient. The net result is that the usable picture, at least as far as ground pattern is concerned, extends only to distances from the pilot approximating to 15 times his height above ground.

This is clearly inadequate for landing a fixed-wing aircraft at representative forward speeds. However, this limitation is of less consequence in the application of shadowgraph techniques to the simulated flying of helicopters when near ground level. Progress is therefore more promising in such applications of the system, more particularly because the shadowgraph picture may be projected from an overhead lamp and model on to a

cylindrical, or part cylindrical, screen surrounding the cockpit; a very wide field of view thus being secured.

A further method of visual presentation is that of the episcope, in which the model is a conventional one strongly illuminated and the picture is projected by a lens system having its entrance pupil at the supposed aircraft position. The problem is that, with a model of reasonably small dimensions, the viewing and projecting equipment must have a very large depth of focus to present, simultaneously, the ground pattern at the lower and upper visibility limits. The specification may require this range to extend from a distance of 30 feet from the pilot's eye to 1,000 yards ahead. To secure this there is no alternative to reducing the entrance pupil of the viewing device almost to pin-head dimensions with the result that the amount of light available for ultimate projection on to the screen will be marginal, even with abnormally high illumination of the model.

The shadowgraph and the episcope methods have the common disadvantage that the spatial relationship of the viewing head and the projection screen must be fixed, which means that apparent changes of heading and attitude have to be provided by movements of the model. This is obviously a formidable mechanical problem. If, however, the model is made small to ease this difficulty, the optical limitation mentioned above is invoked and, in addition, any roughness in the motion system will be unduly apparent at the large magnification involved.

For these reasons, the possible merits of the closed circuit television system have long been realised. Potentially suitable equipment has recently become available at costs no longer prohibitive, and experiments employing this technique are in progress both in the U.K. and the U.S.A. The fact that the camera and projector need not remain in a mutually fixed relationship, and that it is possible to amplify the picture intensity electronically, may eliminate the major disadvantages of the direct optical systems. No doubt this technique will present its own special problems as work proceeds; if colour be regarded as essential in the presentation then considerable additional cost and complication would appear inevitable.

Acknowledgments

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DISCUSSION

AIR-VICE MARSHAL G. SILYN ROBERTS (R.A.F. Bomber Command, *Fellow*): He was glad to open the discussion, particularly as it was at Halton, where over the years so much had been contributed to the foundations and character of the Service in which he served.

He also expressed appreciation of the delivery of the lecture and the able way in which interest had been enlivened throughout the discourse.

Mention had been made of the day landing trainer devised by Mr. Hellings. He recalled flying it some 14 or 15 years ago. It was really delightful to use and gave a most realistic impression of the straight take-off, climb, straight approach and final touch-down. He also recalled the war-time Silloth trainer devised by Wing Commander Iles and wondered whether this work had contributed to the development of modern synthetic trainers. Wing Commander Iles' trainer required the use of a full-scale representative aeroplane and much use was made of mechanism usually found in cathedral organs.

Being at the receiving end, so to speak, he was particularly interested in how many men would be required to keep these modern trainers serviceable and what sort of skill and knowledge they would require.

Finally, having regard to the shortage of electronically-qualified people and the equality of effectiveness of mechanical and electronic computers, he wondered whether there was any reason why more use had not been made of mechanical rather than electronic computers.

MR. MAKINSON: He thought that the best answer they could give to the question about the maintenance of electronic simulators was to quote British European Airways' experience with the Elizabethan and Viscount simulators they had supplied. B.E.A. employed four maintenance engineers of National Certificate Standard full time on the maintenance of these two machines. The standard of serviceability achieved was such that, of the planned fifteen hours per day for five days each week, 85 per cent usage was achieved. Of the fifteen per cent of time not used, seven per cent was lost due to organisational problems in planning the training programme and eight per cent due to unserviceability. "Unserviceability" included any minor defect affecting any one of the simulator functions and did not necessarily imply that the trainer was not in operation.

"Why was not more use made of mechanical computing systems?" He must say they had often asked the same question themselves. However, he thought that there was an answer, and quite a fair one. It would be fairly clear that the mechanical computer

must always be somewhat less versatile than its electronic equivalent, in which the operating characteristic could be readily and radically changed by wiring or component changes. In addition, the mechanical computer rapidly became unduly complex if the equations to be solved involved too many variables. He thought that the short answer was that provided the requirement was relatively simple and well defined, the mechanical computer could more than hold its own both performance and cost-wise, but that beyond a certain stage of complication, certainly before that encountered in a modern flight simulator, the mechanical system began to lose out. However in considering the full range of synthetic training requirements, both systems undoubtedly had their place.

SQUADRON LEADER W. F. DOWSETT (R.A.F., Halton, *Associate Fellow*): Had the lecturers' Company, or allied companies which were associated with flight simulators and computers, used them in any connection with conditions of cabin pressurisation and physical fatigue under conditions of high altitude flying?

A separate question entirely was, whether the idea of simulators and computers which were used for training purposes need necessarily stop at that point and whether in fact they could be extended to cover conditions of research so that, looking ahead rather than looking in terms of current performances, could the lecturers possibly enlighten him and say what possibilities there were for covering future conditions of flying, as well as those which were in existence at the present time?

MR. HELLINGS: Squadron Leader Dowsett asked if they physically provided the changes in cabin pressure in order to induce realistically the fatigue that could accompany that or its malfunctioning. The answer was no; it could presumably be done if it were thought to be sufficiently important, but nobody had asked them to do it yet.

As to the use of these advanced simulators for research purposes, for example to forecast what an aeroplane was going to do before it was built; that was possible only to a very limited extent because a flight computer's behaviour was determined by the parameters which one had decided to build into it, and if these had to be largely guesswork, the behaviour of the simulator would not be a reliable forecast. What one could do was build the simulator more or less concurrently with the aircraft, or shortly after it, when reasonably good estimates were possible of its aerodynamic derivatives and their valuation with such things as configuration and Mach number. It could then be used for working out the best arrangement of controls, cock-pit drills and so forth, and for investigating the probable behaviour of the aircraft in unusual conditions.

GROUP CAPTAIN E. E. VIELLE, O.B.E. (Air Ministry, *Associate*): Having been thoroughly shaken by two prangs in one evening, flying into those trees and then being told to handle this as well, he was naturally a little nervous. He would, however, like to make just one or two points.

First on movement. It was a controversial subject but he was absolutely convinced that movement was highly desirable in the simulator. The reason for that was that unless one had that movement, one tended to feel that one was literally just flying a desk. A little movement in it and it produced far greater realism, even though the movement might not, theoretically, be correct.

It was often said of simulators that it was nothing like flying the aircraft. The chap knew he was on the ground. He did not think that was quite true. Way back, as he thought Mr. Malec would remember, with the Link Celestial Navigation Trainer which was one of the earliest simulators that they had, they found that the navigators were far more frightened of the ridicule of the other chaps watching them than they ever were in the air. In the air they always felt that the pilot would finally pull them out of it. But on the ground they really were for it in this Celestial Navigation trainer. He thought the same was true—it was certainly his experience of simulators—that in fact one got up much more of a sweat in the simulator than one ever did with an instructor in the air. He thought they all knew the story about the, he thought it was on an American, simulator where the instructor was really piling things on until he had got one motor on fire, two others feathered and so on and watching the pilot the instructor himself got so worried that he started strapping on his parachute. That was supposed to be true.

Coming back to movement, and realism, he thought they must be very careful to realise with simulators that in fact they could not reproduce the accelerations they had in the air and, as some of them might know, one of the most dangerous things they had today in flying was the man who was in something with terrific acceleration, who might perhaps be going rather slowly on instruments and then, particularly if he were flying on partial panel, put on full power and immediately get the most extraordinary sensations of looping. Many aircraft were like that. His question therefore was, was there any possible way that they could think of, or that could be devised, that would somehow reproduce to the man in the simulator these accelerations that he sensed in the air, which were, he believed very dangerous indeed?

He had noticed personally, and he thought a lot of other pilots had too, and he believed that the Institute of Aviation Medicine was doing quite a lot of work on this at the moment, that when one got up really high, he meant 50,000 ft. or a little more, one became a different sort of person. One did not react in the normal way that one did lower down, and he believed that if they could find out why that was, which he thought the Institute of Aviation Medicine was trying to do, and then somehow incorporate that sensation or different reaction to instruments into a simulator, he believed it would be extremely valuable. He thought that was particularly important when they got to the higher

flying jet transport aircraft because up to the present this experience was limited to a very few people in the Air Force who had been flying the really high flying aircraft. Was there any hope of somehow reproducing what he thought were potentially dangerous sensations, which he, personally, did not understand at all, but which other pilots as well got when flying at really high altitude?

MR. HELLINGS: As had been said in the lecture, there was no question that pilots did prefer movement, even if it were not theoretically accurate, to a purely static simulator, and there was good reason for this.

Linear accelerations could be simulated. The push-in-the-back acceleration could be suggested by mounting the fuselage so that it could be pushed forward like a swing and held there, when the pilot would feel himself lying back rather heavily in his seat, which he would, he thought, interpret as a forward acceleration as long as his instruments (and any visual effect) supported this. One could do a similar thing laterally to simulate the feeling of a sideways push during an incorrectly co-ordinated turn, and some trainers already did this. Thus in both the fore-and-aft plane and the lateral plane it was feasible to provide quite a strong suggestion of linear acceleration. The sustained "g" one was, so far, in a different category, and it was not easy to envisage a practicable solution.

On the question of anomalous reactions by pilots at high altitude; unless this was due to cabin conditions (which could be reproduced if necessary) the simulator designer would be dependent on the medicos to tell him in what way things seemed different to the pilot. He might then be in a position to simulate this "strangeness" in his simulator as an aid to intensive training or study of the problem.

MR. E. T. JONES: He thought they might get the impression that synthetic training devices started with the advent of the Link trainer. He would like to put that impression right. It had gone wrong. Synthetic training devices started, he thought in so far as operation flying was concerned, as far back as the First World War and Air Vice-Marshal Silyn Roberts in his opening talk did ask why mechanical parts were not used instead of electronic parts. Well, the first ones he thought were related to bombing techniques and they were in general mechanical—handles, levers, gear wheels, and so on, so he thought really, synthetic training devices so far as flying was concerned, started from the operational point of view rather than the training of pilots.

Some Comments on High-Lift Testing in Wind Tunnels with Particular Reference to Jet-Blowing Models

by

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SUMMARY:— This paper considers some of the special problems of wind tunnel testing which arise in high-lift work. Discussion is confined to current experience in the R.A.E. and N.P.L. low-speed wind tunnels, and refers mainly to tests on blowing over flaps or jet-flaps. Comments are made on suitable size of model, methods of feeding compressed air into models without affecting balance readings, and general test technique. Methods of model construction are not specifically discussed.

1. Introduction

This paper discusses some of the special problems in model testing which arise when high-lift applications are involved. Attention is restricted mainly to jet-blowing models, and the discussion is based on the experience gained by the R.A.E. and N.P.L. low-speed wind-tunnel staff in recent tests or in proposed model designs. Comments are made on the factors controlling model size, on test rigs and methods of feeding air to models without applying constraints to the balance, and on the measurement of jet-flow parameters.

Two applications of jet-blowing for high lift are used as illustrations of the problems: firstly, trailing edge flap blowing for boundary layer control, where a relatively small quantity of air, such as might be bled off the engine compressor on an aircraft, is ejected over the upper surface of a conventional flap to prevent flow separation; secondly, the jet flap, where a large quantity of air, representing most or all of the aircraft jet efflux, is blown out at, or near, the wing trailing edge to form a jet sheet.

Other cases where jet blowing improves the lift, which are not specifically covered in this note, are blowing near the wing nose to suppress leading edge separations and the deflection of the ordinary round jet, below the engine nacelle. The problems involved in the wind-tunnel testing of these installations are much the same as in the cases which are to be described here.

Another method of improving the lift is by boundary layer suction at the wing leading edge or over the "knee" of a deflected trailing edge flap. The problems which arise in tunnel testing such models are fully covered by the discussion on jet blowing, apart from the more serious nature of the end effects in two-dimensional testing, which is briefly considered in Section 4, and the detailed design of suction ducts and porous surface, which is outside the scope of the present paper.

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NOTATION

A	area of nozzle sonic throat or exit, sq. ft.
a	local velocity of sound, ft./sec.
c	wing chord
C_D	drag coefficient
C_J	jet thrust coefficient—*see* Section 4.1
C_μ	jet momentum coefficient—*see* Section 4.1 and Appendix V
C_L	lift coefficient
C_l	rolling moment coefficient
C_M	pitching moment coefficient
C_Q	volume flow coefficient $= \dfrac{(m/g)}{\rho_0 V_0 S'}$
g	acceleration due to gravity, 32·2 ft./sec.^{2}
J	jet thrust reaction on the nozzle, lb.
M	local jet Mach number
m	mass flow of jet, lb./sec.
p	static pressure, lb./ft.^{2}
S'	reference area of wing, usually the part which includes the span of the jet, sq. ft
T	temperature, degrees Centigrade Absolute
V_0	wind tunnel test speed, ft./sec.
v	local jet velocity, ft./sec.
x	chordwise distance from leading edge of aerofoil
α	wing incidence relative to free stream, degrees
γ	ratio of specific heats for air
Δh	pressure difference, across flow-meter in terms of height difference on a U-tube
ε	angle of downwash at tailplane, degrees
ρ	density, slugs/ft.^{3}

Suffices

- D stagnation conditions inside the low-velocity model blowing duct. *E.g.* p_D is synonymous with jet stagnation pressure assuming negligible losses in nozzle
- j condition of jet when expanded isentropically to free stream pressure p_0
- 0 free stream conditions
- t conditions at the sonic throat of the nozzle; if subsonic flow, at nozzle exit—*see* Appendix V

2. Choice of Model Scale

There are various conflicting factors which affect the choice of the size of the model relative to the size of the tunnel working section:—

(*a*) Tunnel wall interference, which restricts the model size.

(*b*) Test Reynolds number, model accuracy, insertion of an adequate number of surface pressure tubes, all of which demand as large a model as possible.

(*c*) Other factors which must be considered in conjunction with these, such as the characteristics of the air supply available, model strength, type and size of model support, and methods of feeding compressed air into the model or sucking air out of it.

2.1. TUNNEL WALL INTERFERENCE

Complete models employing boundary layer control by suction, or by blowing small air quantities over flaps, should not present tunnel interference problems much different from those encountered in normal testing because the sectional lift coefficient on the wing is unlikely to exceed about 4. The ratio of wing chord to tunnel height is then usually kept below 1/3, and the ratio of wing span to tunnel breadth below 3/4.

In the case of a jet flap test, however, representing the aircraft approach condition with a C_L of say 10, the tunnel interference corrections assume formidable proportions if we consider a model of the normal size. Since the corrections are inevitably approximate, it will be necessary to set an upper limit on the model size, depending on the accuracy called for in the final evaluation of the test data.

Tunnel interference corrections can be applied in the form $\Delta\alpha$ degrees to the angle of incidence, an additional $\Delta\varepsilon$ degrees to the angle of downwash in the region of a tailplane, and ΔC_D ($=C_L\Delta\alpha/57{\cdot}3$) to the drag coefficient caused by the rotation of the axes of reference through $\Delta\alpha$ degrees. There are also corrections to the effective tunnel velocity, owing to the blockage effects of the model volume and wake drag. In the particular case of very high lift coefficients being considered here, these blockage corrections are not significant factors in choosing the scale of the model and are not discussed further.

To illustrate the importance of tunnel interference corrections, consider a rectangular wing of Aspect Ratio 6, with a full-span jet flap, mounted horizontally in the R.A.E. $11\frac{1}{2}$ ft. $\times$ $8\frac{1}{2}$ ft. closed wind tunnel. For a normal size wing, say 7 ft. span, the tunnel corrections at $C_L=10$ would be the order of $\Delta\alpha=6°$, additional

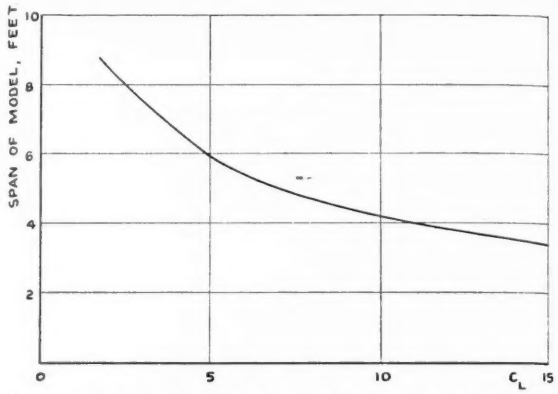

FIGURE 1. Effect of tunnel wall interference on choice of model size. Rectangular wing aspect ratio 6 in $11\frac{1}{2}$ ft. $\times$ $8\frac{1}{2}$ ft., closed jet wind tunnel, correction to α kept to 2°.

$\Delta\varepsilon=4°$, and $\Delta C_D=1{\cdot}1$. Unless such corrections can be worked out accurately using special mathematical treatment for each wing plan form tested, the likely errors in their evaluation are unacceptable.

Figure 1 shows how the size of the model would have to be restricted in a tunnel of these dimensions, to keep the correction $\Delta\alpha$ to 2° at any value of C_L. With corrections of this magnitude it seems likely that, for most wing configurations, the corrections will be sufficiently accurate when based on simple wing theory.

In the case of truly two-dimensional tests on aerofoils, the correction to incidence should only be that due to an induced curvature in the flow. For example, with a 2 ft. chord aerofoil at $C_L=10$ mounted vertically in the $11\frac{1}{2}$ ft. $\times$ $8\frac{1}{2}$ ft. closed tunnel, the value $\Delta\alpha$ is only 1·1°. The model size is more likely to be limited in this type of test by interference of the tunnel wall on the jet sheet emerging from the wing trailing edge.

This jet wall interference will occur on two-dimensional or three-dimensional models where there is a large angle of jet deflection and a large value of jet momentum coefficient. The tunnel wall on the side of the wing lower surface will distort the path of the jet behind the wing, so that it becomes flatter, with consequent reduction in the C_L generated. So far, no theoretical evaluation of this correction is known, and the only known experimental work which is relevant does not cover the range of wall proximities of interest. However, it seems probable that, with a wing chord to tunnel height ratio of about 1/6, a jet flap system, with a 60° angle of jet deflection at the wing, should suffer from only a small percentage reduction in C_L owing to the presence of the tunnel wall. Similar considerations will apply to tests on round jets deflected beneath nacelles, although in this case the corrections may be relatively smaller.

2.2. REYNOLDS NUMBER

The actual size of the model is to some extent fixed by considerations of tunnel wall interference, so that the test Reynolds number is then governed by the choice of test speed (and pressure in a variable density tunnel). The speed, in its turn, may be limited by

strength of the model and supports, by the need to achieve high values of the jet momentum coefficient C_μ (*see* Section 4.1) with a limited compressed air supply, and by Mach number considerations—since at high lifts sonic flow can occur over the wing surface even with low main stream Mach numbers. It is also worth noting that, if the available air supply and hence blowing momentum is limited, the maximum possible test Reynolds number for a prescribed C_μ- value is independent of model scale. Moreover, if C_μ is the parameter governing the effectiveness of blowing, then the maximum possible lift and drag forces on the model are likewise independent of the scale.

A full discussion of what constitutes a desirable value of Reynolds number is not possible in the present paper, but a few comments particularly relevant to high-lift work must be made.

In a complete model test incorporating the ejection of relatively low momentum quantities over orthodox flaps, a test Reynolds number of 4×10^6 based on wing chord can be expected in most cases to give a reasonably close approximation to results at a full scale Reynolds number of 20×10^6, because the full-scale flow will be of the same nature as the flow over the model. This would certainly be true if the wing leading edge were drooped and the wing incidence were not too high so that, with a sectional C_L of 4 say, appreciable nose separation did not occur at either model or full scale. There may be some small scale effect on the quantity of momentum ejection necessary to clear up the flow over the flap, but this is not likely to detract from the value of the test results in most cases. Any unblown part of the wing, and the tailplane, will of course be subject to scale effects of the usual type.

However, jet flap tests, where C_L values of 10 might be envisaged for the approach condition, present an entirely different problem. The size of the model will be small (*see* Section 2.1) and the test speed, also, is likely to be low because of limitations of model strength and pumping facilities. The test Reynolds number in consequence, will probably be less than 1×10^6 in a normal size of wind tunnel. The full scale Reynolds number would also, of course, be relatively low, perhaps 5×10^6, because the aircraft would be moving slowly. However, in this range of disparity between model and full scale conditions, care may have to be taken in the interpretation of the results. The model wing may exhibit a large laminar separation from the leading edge which might not exist, full scale, or at least be different in degree. What effect this would have on a jet flap wing is not yet clear, but the resulting differences in chordwise pressure distribution could affect the position of the centre of pressure and probably the form drag, even though the effect on lift were not large. The tailplane and fin, working at a local Reynolds number of, say, $0{\cdot}3 \times 10^6$ in the tunnel, may give misleading values for their lift slopes, and exhibit early laminar separations which may have to be reduced by roughening their leading edges or by other means. Some attempt to assess the scale effect on fin and tailplane could be made by testing the model at low wing lift, without jet blowing, to as high a tunnel speed as possible, if (as is likely) the tunnel speed is limited in the blowing tests by model strength and pump characteristics rather than by the speed range available. Alternatively, by using an all-moving fin and tailplane on the model, the mean velocity, sidewash and downwash can be deduced and the full scale fin and tailplane effectiveness calculated using estimated full scale lift slopes.

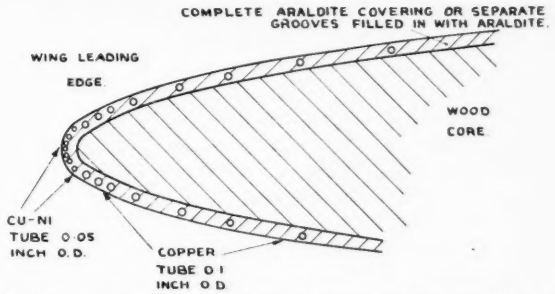
COMPLETE ARALDITE COVERING OR SEPARATE GROOVES FILLED IN WITH ARALDITE.
WING LEADING EDGE
WOOD CORE
CU-NI TUBE 0·05 INCH O.D.
COPPER TUBE 0·1 INCH O.D.

FIGURE 2. Typical installation of pressure tubes around the nose of an aerofoil. All tubes run spanwise, holes are drilled as required into each tube from the wing surface.

2.3. PRESSURE PLOTTING REQUIREMENTS

In a model of small size it may be difficult to fit adequate surface pressure holes to allow an accurate integration to be made for sectional normal force, pressure drag and pitching moments. If such measurements are required, a wise precaution is to attempt a calculation of the expected pressure distribution and plot it against chordwise and normal position in turn. From these curves it is possible to see where the surface pressure should be measured. A large number of positions will be found necessary near the leading edge and on the upper surface near the nose of the flap. As an example, Appendix I gives the positions found desirable in a particular case. In general, between 40 and 60 stations round the aerofoil contour can be regarded as a satisfactory minimum, according to flap pressure-plotting needs.

If there is room, it has been found desirable to lay the tubes at each spanwise station parallel to the span, so that holes can be drilled from the surface into the tube at any required spanwise position (Fig. 2). The advantage of this is that the effect of any suspected fault in the contour of the wing, especially near the leading edge, can be checked by sealing the original holes and repeating the pressure traverse at a different spanwise position. On a small size of model there may be insufficient room near the leading edge for an adequate number of separate tubes, in which case one tube lying in a chordwise direction may be used, and the traverse carried out by the laborious process of drilling various chordwise holes and sealing all but one in turn with grease or wax.

2.4. ACCURACY OF MANUFACTURE

The larger the size of the model, the greater is the percentage accuracy that can be obtained in geometric

dimensions. Certain regions of the model require greater accuracy of manufacture than others; for example, the flow over the undrooped leading edge of a two-dimensional aerofoil might, at high C_L, be very sensitive to small imperfections in the contour, and the angle of incidence at which nose separations occurred could vary markedly at different positions along the span. A satisfactory tolerance of manufacture is very hard to specify, but near the nose it would be advisable to keep within 0·002 in. of the correct contour on a 30 in. chord aerofoil, and the divergence from the true contour should vary smoothly from point to point along the chord so that there are no resulting ridges or flats.

Another region which might be sensitive to imperfections is the nose of the flap, especially if the jet blowing is being applied from the shroud (*i.e.* the main wing ahead of the flap), and if the nose radius of the flap is not large in comparison with the nozzle width. At big flap angles, small imperfections in flap nose contour could precipitate a local separation of the jet from the flap upper surface.

It is known that, in some conditions, the jet effects are sensitive to the size of the air gap between wing and flap and, also, with blowing from the wing shroud, to the height of the flap nose relative to the centre-line of the impinging jet. In such cases, an error of 0·1 per cent chord, *i.e.* 0·03 in. in a 30 in. chord wing, in flap gap or height has been known to affect the answers obtained. It is therefore recommended that tolerances of 0·01 in. should be used in this size of model.

A different case sometimes requiring high accuracy in manufacture is the slot width. Fairly wide tolerances may be good enough in a three-dimensional complete model, where spanwise variations in blown air quantities would probably only slightly modify the total quantity of air required to achieve a given result. However, for two-dimensional work of a fundamental nature, the necessary accuracy is higher and may be difficult to obtain on a small model; for example, in a flap-blowing experiment, the nozzle might be only 0·015 in. wide for a wing chord of 36 in. so that 0·001 in. variation spanwise in the nozzle width could cause 7 per cent variation in momentum coefficient. It is probable that variations of this magnitude are tolerable in two-dimensional work, provided that all divergences in nozzle width occur in a random manner.

3. Various Test-rigs and Methods of Air-feed

3.1. HALF-MODELS

The advantages of using a half-model and reflection plane, compared with a complete model, are that a larger scale of model can be installed, the manufacturing time is considerably reduced, and the model support problem, method of air-feed, and carriage of pressure tubes are all greatly simplified.

The disadvantages are that the model cannot be yawed and the measurements are therefore restricted to lift, drag, pitching moment and, possibly, rolling moment, at zero angle of yaw. There are also some difficulties inherent in the test rig: if a reflection plate

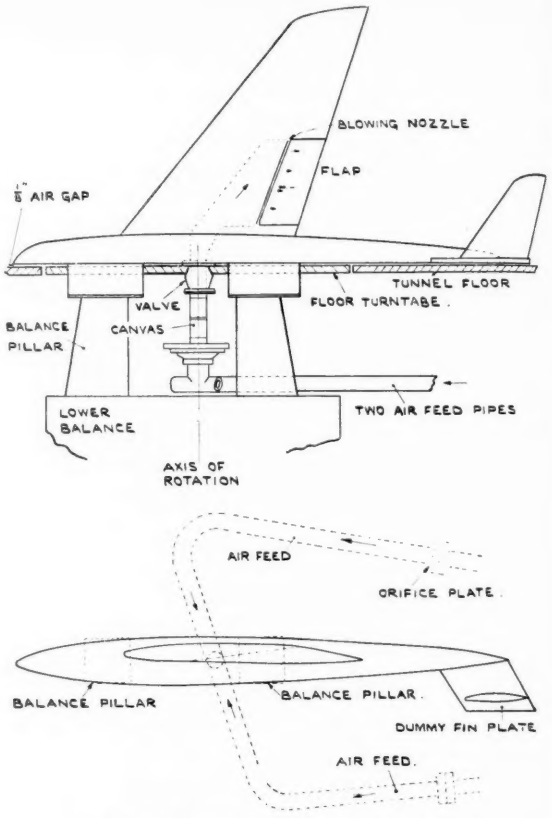

FIGURE 3. Half-model rig in R.A.E. wind tunnel.

is used the calibration of the tunnel may present problems akin to those met with two-dimensional models between end-plates (*see* Section 3.3). If the model is mounted directly on the tunnel wall or floor, tunnel speed calibration will be simple, but the relatively thick wall boundary layer may affect the forces on the half-fuselage or the lift slope of the half-tailplane. This can be improved by sucking most of the boundary layer off the tunnel wall in the region of the model (*see* also Section 3.3 for the case of aerofoil tests).

In general, the type of air connection used to feed air into the model without balance constraint will be largely a matter of taste, and will depend on the available space and the type of balance employed. If the blowing pressure is relatively low, a mercury seal is attractive, but its basic simplicity is offset by the vertical height necessary and appreciable weight involved for the blowing pressures of most investigations. Two other schemes, as applied to current R.A.E. and N.P.L. test rigs, will therefore be described in some detail.

A typical rig of a half-model on the floor of the R.A.E. 11½ ft. × 8½ ft. wind tunnel is shown in Fig. 3. The model is mounted with a ⅛ in. air gap between the fuselage centre plane and the tunnel floor. The model is connected to the balance underneath the tunnel by two pillars, and the compressed air for the

jet blowing is fed vertically upwards on the axis of model and balance rotation. The compressed air is led from the pumps along two horizontal feed-lines which come together under the model; the advantages of a double feed are, firstly, that there is no side-thrust on the vertical part of the final air feed system into the model, and, secondly, two orifice plates or flowmeters can be used simultaneously to measure the mass flow, so that if one develops a fault it is immediately noticed. The vertical air feed into the model and flexible coupling are shown in Fig. 4 and described in Appendix II. After numerous experiments the final choice of material for the flexible coupling has been rubberised canvas, necked slightly at mid-length by a restraining ring in order to assist flexure when under pressure. Balance zeros are taken with the valve F, in Fig. 4, closed, and the system raised to the same static pressure as occurs in the actual tests. The valve is fully opened for the test runs. The effect of the rubberised canvas link on the balance zeros depends on the pressure, and the canvas wall is made as thin as possible to minimise its constraining effects on the balance. Typical readings of balance zeros are given in Appendix II. The zero changes are very small and are repeatable with time, so that the inaccuracies in the final readings are negligible.

As an alternative to a canvas hose connection, an air-bearing connector has been developed at the N.P.L. for feeding air (blowing or suction) into models without constraint on the balance. Fig. 5 illustrates the principle as applied to a half-model suspended horizontally from the three-component overhead balance in the N.P.L. 13 ft. × 9 ft. closed wind tunnel. There is a clearance of less than 0·2 in. between the fuselage centre-plane and a large false wall mounted vertically in the working section. (The false wall is omitted in Fig. 5 for the sake of clarity).

The air-bearing connector is located inside the tunnel on the other side of the false wall from the model*. The central, or floating link, of the connector is attached to the model by the delivery pipes and is also suspended from the overhead balance as shown in Fig. 5. Two independent air feeds can be taken to the model; for example, one can be used for trailing edge flap blowing and one for wing nose blowing. The floating link is constrained in lateral, rolling and yawing movement by two air-bearing pads, shown in Fig. 6 but not Fig. 5, which are rigidly connected together and earthed to the tunnel structure so as to leave 0·002 in. clearance between the adjoining pad and floating link faces (*see* Fig. 6). The central axis of the pads and the link are lined up with the pitching axis of the model. The two separate air supplies for the model are fed into the air-bearing connector at opposite ends of this axis; the air-bearing pads are supplied quite independently. The design and performance of the air-bearing connector is discussed further in Appendix III.

*With a model mounted close to the tunnel wall (or floor), the air-bearing connector could of course be located outside the tunnel working section.

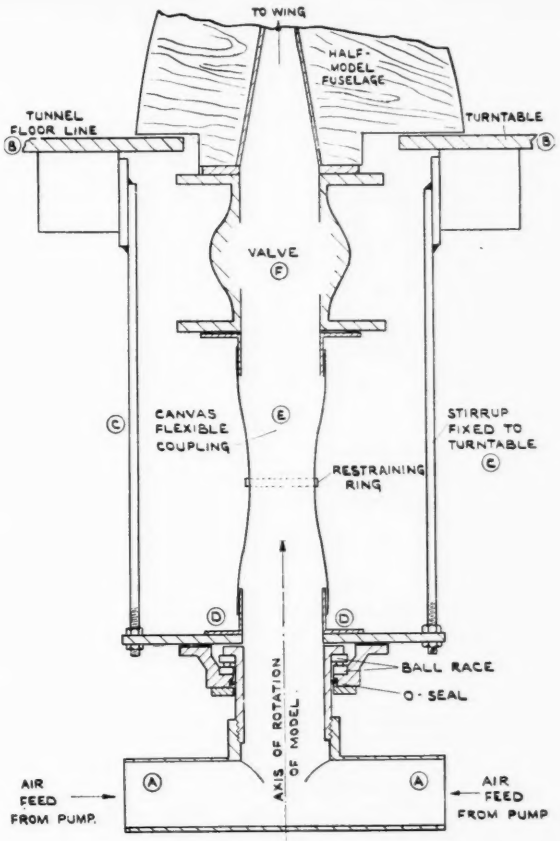

FIGURE 4. Details of air-feed to half-model. R.A.E. wind tunnel (*see* Appendix II for description).

With the type of half-model rig considered, using a large false wall down the middle of the working section, care has to be taken to ensure a uniform velocity field inside the new effective working section. The variation in mainstream velocity from roof to floor, with a vertical false wall, is not likely to be much larger than usual. But the variation along wind and across wind can be significant close to the false wall, if the blockage on the two sides becomes very different. It should be possible to improve this by putting an adjustable flap on the trailing edge of the false wall and hence controlling the proportion of the mainstream which is fed into either half of the working section. Some further discussion of false walls or endplates is given in Section 3.3 in relation to two-dimensional testing.

3.2. COMPLETE MODELS

The advantages of using a complete model compared with a half-model are obvious, in that all six components of force and moment can be measured in any desired combination of pitch and yaw. However, in addition to a possible decrease in model scale, difficulties arise with complete models in the design of the supports and methods of air supply for jet blowing. The model rig used will depend on the type of balance and characteristics of the air supply available. If there

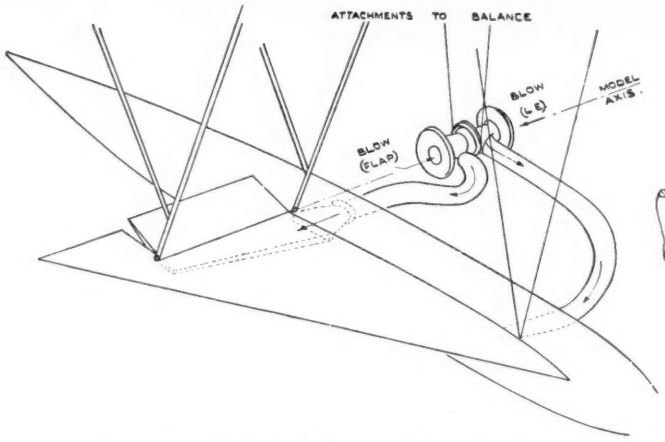

FIGURE 5. Half-model rig in N.P.L. wind tunnel. The air-bearing pads (Fig. 6) and the false wall (Section 3.1) are not shown).

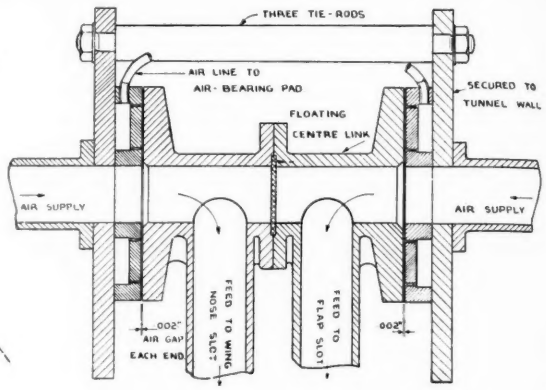

FIGURE 6(*a*). Details of air-feed to half-model. N.P.L. wind tunnel (*see* Appendix III for description).

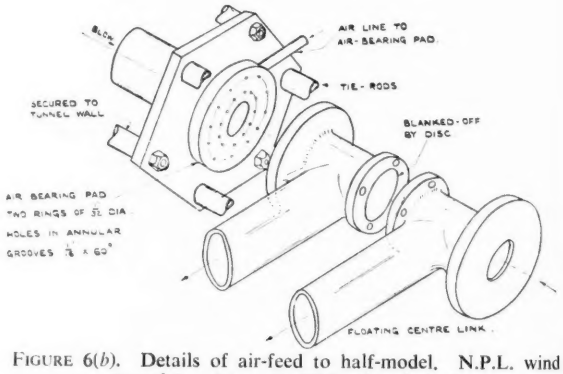
BLOW
AIR LINE TO AIR-BEARING PAD
TIE-RODS
SECURED TO TUNNEL WALL
BLANKED-OFF BY DISC
AIR BEARING PAD
TWO RINGS OF 5/32 DIA HOLES IN ANNULAR GROOVES 3/8 X 60°
FLOATING CENTRE LINK

FIGURE 6(*b*). Details of air-feed to half-model. N.P.L. wind tunnel (*see* Appendix III for description).

is pressure to spare in the air feed, so that pipe losses are not important, an attractive way would be to mount the model on a rear sting and strain-gauge balance, capable of rolling and pitching, and to feed the jet-blowing air down the centre of the sting. Little experience of jet-blowing on complete models has so far been gained at the R.A.E. and N.P.L., but two possible arrangements are being considered in conjunction with the existing mechanical balances.

The arrangement shown in Fig. 7, with an air-bearing type of connector housed inside the model fuselage, is contemplated for tests on blowing over flaps. Lift, drag and pitching moment, only, are to be measured, using an overhead three-component balance. The air-bearing connector works on the same principle as that already described in some detail for half-models (*see* Section 3.1 and Appendix III), its axis being in line with the pitching axis of the model. In the present case, however, the air supply for the model is fed into the central part of the connector down a single fixed pipe, and the air-bearing pads (supplied independently) are also on this central part. The floating faces form the outer part of the connector and are rigidly attached to the model, so that twin feed pipes can supply the flap

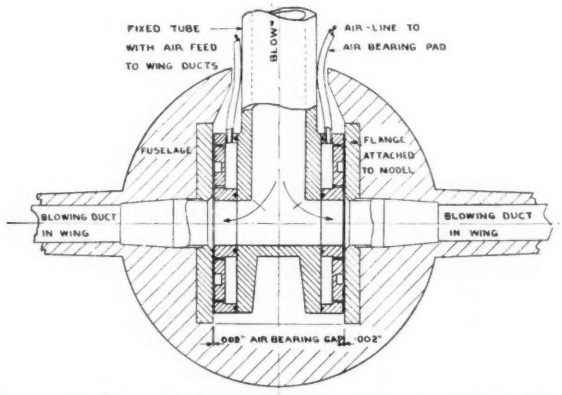

FIGURE 7. Proposed air-bearing connector in complete model. N.P.L. wind tunnel.

blowing air to each wing. A further development of the scheme is envisaged, incorporating additional air-bearings at right angles to the first pair, so that six-component measurements can be made and the model yawed as well as pitched.

In the case of another complete model, representing a jet flap aircraft where large values of C_L are envisaged, the model is too small and the flow quantities too large for a suitable air-bearing type of connector to be fitted inside the fuselage. The model is therefore supported on a single strut which also carries the air supply, and some type of flexible coupling or air-bearing connector will be housed outside the tunnel. The strut has to have an appreciable cross-sectional area to carry the required quantity of compressed air, and will have to be about 40 per cent thick in order to keep its chord small relative to the wing chord. By yawing the strut relative to the model, it is hoped to set the strut at "zero lift" in the sidewash field of the model (using strut surface pressure measurements), and thereby to minimise strut interference.

3.3. TWO-DIMENSIONAL AEROFOIL MODELS

3.3.1. *End-plate design*

Two-dimensional characteristics are obtained in a wind tunnel by testing a finite span of the aerofoil

section in between reflection planes. If the tunnel has been specially designed for two-dimensional work, the working section will have a relatively large height/width ratio, and the tunnel walls will form the reflection surfaces. This is in many ways the best type of rig because the reflection planes are of near-infinite extent and also the velocity calibration of the tunnel presents no unusual problems.

In many general-purpose wind tunnels, however, it is often impracticable to carry the aerofoil right through from wall to wall, because of limitations of model strength and air supply, and therefore separate end-plates have to be used. They can be employed basically in one of two ways.

The first method is to bridge the tunnel completely from roof to floor (assuming a horizontal model) with large false walls which are continued well downstream of the model. The effective aspect ratio of the model is then certainly very large, but considerable difficulty can arise in calibrating the velocity of the new working section. Virtually, we now have one wind tunnel inside another, so that unless suitable precautions are taken, the distribution of the mainstream flow between the three sections of the tunnel working section will vary appreciably as the model lift and drag are altered. It may be possible to hold the velocity constant in the centre section which contains the model, by adjustment of trailing edge flaps on the false walls (*see* also Section 3.1 for half-models), but it may also be necessary to ensure that the flow into the centre section is reasonably uniform. Most of these difficulties could of course be avoided by fitting a complete "two-dimensional" contraction and diffuser to the false walls so that the whole of the mainstream flow would pass through the centre section. However, care must then be taken to ensure that flow separation in the diffuser does not occur and that the performance of the tunnel fan is not seriously impaired.

The second method is to use much smaller end-plates which do not span the tunnel, so that the working section is not divided into separate air channels, and hence tunnel velocity calibration is not much more difficult than with a normal type of model; there is the added advantage of greater accessibility. However, the aerofoil is only quasi two-dimensional in such conditions; the chordwise distribution of surface pressure is practically independent of spanwise position, but the model has an "effective aspect ratio" because downwash effects reduce the lift-incidence slope below the two-dimensional value and provide an induced drag contribution to the pressure drag. A thorough investigation of such end-plates in relation to high-lift models has not so far been made, but some tentative suggestions for suitable end-plate size are put forward in Appendix IV.

3.3.2. *End-effects at the aerofoil wall junctions*

Wall boundary layer separations and flow through an air gap are two possible sources of trouble at the junction between the end of the aerofoil and the adjoining wall of the reflection plane.

Wall boundary layer separations can be precipitated by the very large adverse pressure gradients which occur on the wing upper surface at high lift coefficient. The separated region spreads spanwise in a triangular wedge over the aerofoil surface and may result in a considerable loss of lift and in spurious profile and induced drag. The overall effect on balance readings will obviously be minimised by making the geometric aspect ratio of the model as large as possible. Even on a purely pressure-plotting model, a pressure traverse near mid-span can be affected by the separations, because the spanwise distribution of lift is no longer uniform. Separations of this type have been observed on plain aerofoils at high incidence and in systems where high lift coefficients are attained by suction at the nose of the wing or by suction at the "knee" of a deflected trailing edge flap. The trouble can be alleviated, if not cured, by auxiliary boundary layer control on the walls themselves, either by suction through the walls, or by blowing a high-energy air jet along the wall out of a narrow slit close to where separation begins. Fixed turning vanes mounted on the wall near the flap "knee," or fences on the aerofoil itself, have also been known sometimes to improve matters. In flap-blowing or jet flap tests, however, the separations are likely to be less significant than they are with suction or uncontrolled wings, because the jet flow will re-energise the wall boundary layer. It is suggested that the geometric aspect ratio of the model should never be less than unity and, preferably be considerably larger.

An additional end-effect can be caused by the small air gap which is sometimes left between the end of the aerofoil and the adjoining wall, to avoid frictional interference with balance readings. Any appreciable leakage of air from lower to upper surface through the gap may result in local lift losses and the appearance of drag terms, similar to those caused by wall boundary layer separations. This trouble is particularly likely to occur in high-lift work because of the large pressure differences between the two wing surfaces. A compromise has to be reached where detailed pressure-plotting on the model shows that the aerodynamic effects of the gap have been minimised, while the gap is still large enough for the balance to function with adequate freedom. It may be possible to achieve this, for example, by fitting an inflatable rubber seal at the wing-wall junction and finding by experiment the optimum seal pressure; other methods involve filling the air gap with very soft felt, or similar material. The problem of the air gap should not arise, of course, in pressure-plotting work, because there is no need to have an air gap in this case; nor will it arise in balance work if the end-plates have been mounted integrally with the aerofoil on the balance system, although an allowance for tare drag will be needed unless the end-plates are relatively small.

4. Measurement of Jet-flow Parameters

4.1. DEFINITION OF THE MAIN PARAMETERS

In flight applications of blowing for boundary layer control (nose or flap blowing), only a fraction of the

mass-flow through the jet-engine compressor is normally bled off, while the available pressure ratio may be as much as 5:1. In the case of a jet flap aircraft, where practically all the jet-engine efflux may be involved, the pressure ratio is more likley to be about 2:1. With either scheme of blowing, the full-scale total temperature at the wing nozzle may be of the order of 300°C.

On a wind tunnel model, it is rarely found practicable to reproduce the full-scale temperature, and clearly the range 15°C to 50°C is preferable from a constructional standpoint, in order to avoid the need for special materials, and to cope with differential expansions. The maximum pressure of the air may also be restricted to less than the full-scale value by the characteristics of the pumps, by the strength of the flexible couplings between the model and the pipe-line, or by the strength of the ducts inside the model itself.

The jet momentum is generally assumed to be the main factor governing the effectiveness of blowing, while the actual values of the jet velocity and temperature are normally assumed to be of only secondary importance. Some support for these assumptions is available from tests on the downwash induced by a round jet issuing obliquely to the main stream, and on blowing over a wing trailing edge flap for the prevention of flow separation. Hence, for many experiments, the blowing air need not be fed into the model at the same pressure and temperature as full scale. However, further justification is desirable when very large momentum rates are involved, as in the case of jet flap experiments. It should be noted that, in any case, if the air intakes associated with the full-scale propulsion system are also to be represented on the model, then the correct intake velocity ratio and mass flow will have to be obtained on the model in order to achieve the correct effects at the intake, irrespective of the rules governing the way in which jet-blowing can be represented.

The momentum coefficient used for the correlation of blowing results is now usually defined as

$$C_\mu = \frac{(m/g)\, v_j}{\frac{1}{2}\rho_0 V_0^{\,2} S'}$$

where m is the measured mass-flow rate (lb./sec.);
v_j is the theoretical jet velocity (ft./sec.) reached on isentropic expansion from the stagnation pressure p_D in the wing duct to free-stream p_0;
S' is the wing area (sq. ft.) normally taken as corresponding to the spanwise extent of the jet-blowing; and
$\frac{1}{2}\rho_0 V_0^{\,2}$ is the free-stream dynamic head (lb./sq. ft.).

In early work on boundary layer control, where the pressure ratio p_D/p_0 was close to unity, incompressible flow was often assumed and the jet velocity v_j was taken as

$$v_j = \frac{(m/g)}{\rho_0 A_t}$$

where A_t is the area of the slot exit and ρ_0 is the free-stream density (slugs/cu. ft.). For pressure ratios less than about 1·2: 1, this gives values of v_j, and therefore C_μ, within 5 per cent of the values obtained by the usual definition assuming isentropic compressible flow.

In jet flap work, a jet reaction coefficient

$$C_J = \frac{J}{\frac{1}{2}\rho_0 V_0^{\,2} S'}$$

is sometimes employed, where J is the total jet reaction in lb. thrust at the nozzle exit. On wind-tunnel models this is often derived experimentally by pitching the model until the axis of the jet coincides with the drag axis of the balance; the thrust is measured on the balance with the wind off, and a correction is added to allow for the pressure drag round the model arising from the flow induced by the jet stream. For convergent nozzles at pressure ratios above the critical, 1·89, the value of the jet reaction coefficient C_J derived by isentropic flow theory is slightly smaller than the corresponding theoretical value of C_μ, because the expansion inside the nozzle is incomplete; but even at a pressure ratio of 5 the difference in the calculated values of C_J and C_μ is only about 3 per cent. We might expect, therefore, that when C_J is obtained in a test by direct thrust measurement, as described above, the measured C_J should only differ by a few per cent from the C_μ-value determined from the measured mass-flow rate and the theoretical "expanded" jet velocity.

4.2. EXPERIMENTAL DETERMINATION OF C_μ

The theoretical expanded velocity v_j is a function of the stagnation pressure p_D in the low-velocity wing duct, and is independent of nozzle area. The formula for v_j is given in Appendix V, equation (2). The stagnation pressure p_D can be measured, at zero tunnel wind speed, by inserting a small Pitot tube through the nozzle into the low-velocity region immediately upstream of the throat, and a series of Pitot readings can be taken to assess the spanwise distribution of total head. A single pressure tapping (or more than one, in case one leaks), placed at any convenient position inside the model duct, is then calibrated against the nozzle Pitot reading. Thereafter, the duct pressure tapping is used to set the flow, wind on. If the duct velocity is only a small fraction of the blowing velocity, the nozzle Pitot and the duct pressure tapping will give practically the same readings.

Mass flow is readily measured by an orifice plate or similar device in the pipeline between pump and model. If the type of flexible coupling or gland, used to feed the air supply into a balance-mounted model, is not entirely leak-proof, the leak has to be calibrated or else the mass-flow measured on the model side of the leak. Mass flow can also be evaluated theoretically from the value of stagnation pressure p_D, duct temperature T_D, and nozzle throat area A_t, on the assumption of isentropic flow through the nozzle (*see* Appendix V equation (4)). In general, the measured and theoretical values should agree within a few per cent, provided that the slot area can be measured accurately, and the pressure ratio is not too small. Accuracy of measurement is discussed further in Appendix V.

For a given pressure ratio and nozzle area, the value of C_μ will be independent of stagnation temperature and therefore, if m and v_j are both calculated from p_D,

it is unnecessary to control the jet temperature closely, or even to know its value. If only v_j is calculated theoretically, and the mass flow m is determined separately from orifice plate readings, for example, then the evaluation of C_μ requires a knowledge of duct temperature T_D (Appendix V equation (3)); this is best derived by inserting a thermo-couple inside the model duct. Since, probably, in all methods of measuring mass flow in a pipe there is a similar temperature term, the product mv_j is again independent of temperature, so long as the temperature at the orifice plate and at the entry to the nozzle are closely the same.

Trouble can arise in blowing experiments from moisture in the air supply. On a full-scale aircraft, moisture is present, but the temperature is probably too high for moisture effects to be significant. On a model, however, if the jet temperature is kept relatively low moisture can have unfortunate effects, for if the cooling of the air in the expanding jet results in condensation the effective value of C_μ is altered. Moisture can also effect the calibration of orifice plates, while water drops tend to form and block the pressure tube connections from the orifice plate to the manometer. The effects naturally become worse with increase of pressure ratio and decrease of stagnation temperature. Since the drying of appreciable quantities of air requires a considerable outlay on equipment, it is often found necessary to use undried air. In this case it is desirable to work at as low a pressure ratio as possible, and keep the stagnation temperature as high as structural considerations permit. In the R.A.E. test rig the air is cooled after leaving the compressor, free water drained off, and the air then re-heated electrically. The air temperature in the model is around 50°C. In the N.P.L. test rig, dry compressed air is obtained from the high-speed tunnel storage tanks and passes through a pair of reducing valves in series; the temperature in the model duct is closely the same as that of the tunnel free-stream.

A range of C_μ values can be obtained on the model by variation of tunnel speed, variation of nozzle width, or variation of pressure ratio. Variation of wind speed is a very simple way of changing C_μ, but, since it involves a change in Reynolds number, the validity of this method has to be considered in relation to the specific type of model being tested. Variation of nozzle width is a desirable feature to incorporate in most models, especially if the range of pressures available is limited, and it has the advantage that the spanwise distribution of jet efflux can readily be controlled; however, it obviously complicates the model design. Variation of pressure ratio is a very convenient way of changing momentum flow, and is acceptable so long as it involves no secondary complications in regard to Coanda effects or mixing losses. In general, the higher the pressure ratio, the less is the mass flow to achieve a given value of C_μ, and hence the smaller the spanwise duct losses; this may be an important consideration if there is little room to spare in the model for ducts. At high pressure ratios the jet will be supersonic, but there is no conclusive evidence to show that there are any large differences in the final aerodynamic effects, whether a given C_μ is obtained on a model by a subsonic or a supersonic jet; this fact may help to simplify the attainment of a large range of C_μ values in a test programme. It should be remembered, however, that if the jet is choked in the nozzle, the mass flow emerging will become independent of any small variations in the external static pressure field along the wing span, whereas with subsonic blowing it will not.

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APPENDIX I

Suitable Location of Surface Pressure Points

The wing is assumed to be of symmetrical section and fitted with a 25 per cent chord trailing edge flap. Experience has shown that the positions suggested in Table I should be adequate, in high-lift testing, for the evaluation of the pressure lift and pitching moment and for general exploration of the surface pressure distribution. Additional points might be required within the first 0·01 chord from the leading edge for precise determination of the location and magnitude of the forward suction peak, and also for accurate evaluation of the pressure drag.

TABLE I

Chordwise position, x/c, as a function of the wing chord

Upper surface	*Lower surface*	*Upper surface*	*Lower surface*
0	—	0·6	0·6
0·0025	0·0025	0·65*	—
0·005	0·005	0·7	0·7
0·0075	0·0075	0·725*	0·725*
0·01	0·01	0·75*	0·75*
0·015	0·015	0·76*	—
0·02	0·02	0·77*	—
0·035	0·035	0·78*	—
0·05	0·05	0·79*	—
0·075	0·075	0·8	0·8
0·1	0·1	0·825*	—
0·15	0·15	0·85*	0·85*
0·2	0·2	0·9	0·9
0·3	0·3	0·95	0·95*
0·4	0·4	1·0	—
0·5	0·5		

*Points marked thus would be unnecessary if no flap were fitted. If a flap is fitted, however, extra points would be needed around the flap nose at not less than 10° intervals. For example, 4 extra points for a 40° flap deflection angle.

APPENDIX II

Details of Air-Feed, R.A.E. Half-Model

(*see also* Section 3.1 and Figs. 3 and 4)

In Fig. 4 the two feed-pipes A and the final vertical feed into the model form a T-junction on the axis of model rotation.

TABLE II

Model α *degrees*	*Pressure inches* Hg	$\triangle L$ *lb.*	$\triangle C_L$	$\triangle D$ *lb.*	$\triangle C_D$	$\triangle M$ *lb. ft.*	$\triangle C_M$
0	30	1·7	0·002	3·39	0·0047	1·9	0·0008
	60	4·4	0·006	3·77	0·0052	4·8	0·0020
16	30	2·3	0·003	2·54	0·0035	2·0	0·0009
	60	5·6	0·008	3·30	0·0046	4·4	0·0019

When the model is rotated through a range of incidence, the turntable B set in the floor of the wind tunnel is rotated independently of the model. From the turntable the stirrup C is attached so that the flange D at the lower end of the flexible coupling also rotates. The flexible coupling E therefore remains untwisted throughout the incidence range. The rotation of the flange D relative to the T-junction beneath it is effected without leakage by the ball race and O-seal shown in the diagram.

Leakage is negligible so that the mass flow of the air being blown over the flaps can be measured by orifice plates in the horizontal feed pipes between the compressors and the T-junction.

The rubberised canvas flexible coupling is normally about 10 in. long and 4 in. diameter. Balance zeros are obtained by closing the valve F fixed to the model and applying the working pressure to the air-feeds below the model. Table II gives typical values of the change in balance zeros on applying pressure.

The coefficients C_L, C_D, C_M are based on the typical size of wing and value of test speed (200 ft./sec.) normally used in such tests. These balance zeros have been found to stay consistent from day to day and are applied to all test measurements.

On the R.A.E. lower balance, with a virtual-centre movement about mid-tunnel height, the rolling moment changes are directly proportional to the lift force changes, ΔL, given in Table II. The effect is to give changes ΔC_l in rolling moment coefficient zeros equal numerically to about half the zero changes ΔC_L shown in Table II.

APPENDIX III

Details of Air-Bearing Connectors; N.P.L. Models

The general arrangement of the air-bearing connectors for lift, drag and pitching moment measurements on half-models and complete models have been given in Sections 3.1 and 3.2, and Figs. 5, 6 and 7. The air-bearing pads, designed on the basis of unpublished R.A.E. results, have two concentric rings of twelve 1/32 in. diameter holes in vee-grooves 1/16 in. wide and of 60° included angle. The internal and external diameters of each pad (and also of the floating-link faces which oppose them) are 2 in. and 6 in. respectively, giving a face area of roughly 25 in.² each. Bench tests have shown that the system can withstand a lateral force of more than 100 lb. on the floating link with a pressure of only 10 lb./in.² (gauge) applied to the air-bearing pads.

In current work, the pad pressure is usually set at 35 lb./in.² (gauge), partly for convenience and partly to ensure that the floating links remain perfectly free under any rolling or yawing moments that are likely to occur. At this pad pressure, lateral loads of up to 300 lb. should be adequately withstood. The system has worked satisfactorily with up to 55 lb./in.² supplied to the floating link.

In the example of the twin-feed floating link shown in Figs. 5 and 6 for the half-model, if only one of the feeds to the model is required, it has been found advisable to apply the same pressures at both inlets to the floating link and block one of the outlets. If one of the link inlets is fed with jet-blowing air at a much higher pressure than the other, then different pressures may have to be supplied to each air-bearing pad. In fact, it may be entirely unnecessary to supply the pad on the same side as the higher pressure inlet.

The air consumption of the two pads at a pressure of 35 lb./in.² (gauge) was about ½ cubic ft./sec., free air delivery, in some typical tests with no pressure applied to the main jet-blowing feed lines. This quantity was halved when the pad pressure was dropped to 10 lb./in.² About half of the pad air escaped via the main outlet feed-pipes to the model when the main jet-blowing pressure was zero. As the jet-blowing pressure was raised, the leak into the model pipe-lines steadily decreased. The leak was in any case of little concern, because the total amount of air supplied to the model, and its pressure, could be derived from a Pitot-static or orifice plate measurement in the feed lines between the floating link and the model; these instruments could be calibrated quite easily, on site, by sealing the air-bearing gap.

APPENDIX IV

Suggestions for the Size of End-Plates

These notes refer to the finite-sized end-plates which give quasi two-dimensional conditions on aerofoil models, as discussed in Section 3.3.1. The effect of end-plate size on high-lift models has not been studied systematically, so far as is known. Hence the suggestions made here, which are based on current experience at the N.P.L., should be regarded as tentative.

With aerofoil models employing boundary layer control for high lift, *i.e.* blowing or suction giving lift coefficients of the order of 4, end-plates extending two-thirds chord ahead of and behind the model have in general proved adequate. Larger extensions upstream are objectionable in that they lead to thicker wall boundary layers, and the subsequent dangers of boundary layer separation discussed in Section 3.3. The total end-plate height normal to the plane of the model (at zero incidence) should probably not exceed half the tunnel height, in order to avoid the effects of tunnel compartmentation on the mainstream velocity calibration. Large rotating fairings, inserted between the end-plates and the tunnel walls to maintain a sensibly uniform lift loading across the whole working section, would increase the effective model aspect ratio. However, they can introduce both aerodynamic and handling difficulties themselves, particularly when tests are being made under a wide range of conditions not previously explored.

In jet flap testing, where much larger values of lift coefficient may be involved, and strong jets issue near the aerofoil trailing edge, the size of the end-plates relative to wing chord needs to be increased. No definite recommendations are possible at present, but suggested values are:

1½ chords upstream of the leading edge, 4 chords downstream of the trailing edge, 1½ chords above the chord-line, 3 chords below. Since the aerofoil chord, itself, must be small to avoid large tunnel corrections (Section 2.2), the end-plate height can still be considerably less than the working section height.

Mangler's end-plate theory* gives the effective aspect ratio of an aerofoil between end-plates, as a function of the geometric model aspect ratio and the ratio of aerofoil span to end-plate height. The lift-incidence curve slope obtained by mid-span pressure plotting has been found to agree fairly well with estimates from two-dimensional data, using a correction to incidence based on this calculated effective aspect ratio.

APPENDIX V

Formulae for Momentum Coefficient, C_μ, and Notes on Accuracy of Measurement

The blowing jet momentum coefficient is defined as

$$C_\mu = \frac{(m/g)\, v_j}{\frac{1}{2}\rho_0 V_0^{\,2} S'} = 2C_Q \frac{v_j}{V_0} \quad . \quad . \quad (1)$$

(*see* Section 4.1 for discussion). The velocity, v_j, is based on expansion to free-stream pressure. The temperature in the jet, after such expansion, can be markedly different from free-stream temperature, but this is normally ignored.

The velocity v_j is given by

$$v_j = a_D \left[\frac{2}{\gamma - 1} \left\{ 1 - \left(\frac{p_0}{p_D} \right)^{\frac{\gamma-1}{\gamma}} \right\} \right]^{\frac{1}{2}}$$

where a_D is speed of sound, and p_D stagnation pressure, in the low-velocity model duct.

With $\gamma = 1{\cdot}4$ and $a_D = 1117 \left(\frac{T_D}{288} \right)^{\frac{1}{2}}$ ft./sec., where T_D is the stagnation temperature (degrees Centigrade Absolute) in the model duct, it follows that

$$v_j = 147{\cdot}1\,(T_D)^{\frac{1}{2}} \left\{ 1 - \left(\frac{p_0}{p_D} \right)^{\frac{2}{7}} \right\}^{\frac{1}{2}} \text{ ft./sec.} \quad . \quad (2)$$

Case (A): Mass Flow Measured Directly

If the mass flow of the blown air is measured directly in the pipe-line, as m lb./sec. and $\frac{1}{2}\rho_0 V_0^{\,2}$ is specified in lb./ft.^{2} (*i.e.* ρ_0 in slugs/ft.^{3}) then

$$C_\mu = \frac{(m/g)}{\frac{1}{2}\rho_0 V_0^{\,2} S'} \cdot 147{\cdot}1 \cdot (T_D)^{\frac{1}{2}} \left\{ 1 - \left(\frac{p_0}{p_D} \right)^{\frac{2}{7}} \right\}^{\frac{1}{2}} \quad (3)$$

When m is measured by an orifice plate or Pitot-static traverse in the delivery pipe,

$$m \propto \frac{1}{(T_m)^{\frac{1}{2}}} \cdot (\Delta h)^{\frac{1}{2}}$$

where T_m = absolute temperature at the measuring point and Δh = reading of the flow-measuring manometer (for example, inches of water).

Hence $$C_\mu \propto \frac{(T_D)^{\frac{1}{2}}}{(T_m)^{\frac{1}{2}}} \cdot (\Delta h)^{\frac{1}{2}}$$

Therefore, if T_D and T_m are within 2 per cent of one another, say 6°C for a stagnation temperature around 50°C (*i.e.* 323° Absolute), the difference in temperature can be ignored to an accuracy of 1 per cent in C_μ, and the C_μ-value is independent of the air temperatures used.

Case (B): Mass Flow Calculated from Nozzle Area

When m is calculated theoretically on the assumption of isentropic flow in the nozzle, it is convenient to consider separately pressure ratios $\frac{p_D}{p_0}$ above and below the critical value for choked nozzle flow.

(*i*) *Supersonic jet flow.* In this case, $M = 1$ at the effective throat of the nozzle, and this governs the mass flow.

Hence $$(m/g) = \rho_t A_t v_t$$

where A_t is the throat area, and the velocity v_t and density ρ_t are appropriate to sonic conditions.

Consequently

$$(m/g) = \rho_D a_D A_t \left\{ \frac{2}{\gamma + 1} \right\}^{\frac{\gamma+1}{2(\gamma-1)}}$$

Suffix D refers to conditions in the low-velocity model duct; or strictly, to stagnation conditions at the entry to the nozzle inside the wing.

With $\gamma = 1{\cdot}4$, and assuming the wind tunnel has a working section at atmospheric pressure, the relation for m can be reduced to

$$m = 49{\cdot}5 \left(\frac{288}{T_D} \right)^{\frac{1}{2}} \left(\frac{p_D}{p_0} \right) . A_t \text{ lb./sec.} \quad . \quad (4)$$

From equations (1), (2) and (4)

$$C_\mu = \frac{3{\cdot}84 \times 10^3}{\frac{1}{2}\rho_0 V_0^{\,2} S'} \cdot A_t \cdot \left(\frac{p_D}{p_0} \right) \left\{ 1 - \left(\frac{p_0}{p_D} \right)^{\frac{2}{7}} \right\}^{\frac{1}{2}} . \quad (5)$$

The expression is dependent only on the pressure ratio $\frac{p_D}{p_0}$, the temperature term disappearing.

(*ii*) *Subsonic jet flow.* In this case the pressure at the nozzle exit is taken as p_0, the free stream pressure,* and the exit velocity is given by the expression for v_j of equation (2).

Hence $$(m/g) = \rho_t A_t v_j$$

where suffix t denotes conditions at the slot exit. From this,

$$(m/g) = \rho_D a_D \left(\frac{p_0}{p_D} \right)^{\frac{1}{\gamma}} \left\{ \frac{2}{\gamma - 1} \left(1 - \frac{p_0}{p_D} \right)^{\frac{\gamma-1}{\gamma}} \right\}^{\frac{1}{2}} .$$

With $\gamma = 1{\cdot}4$, and assuming as before an atmospheric wind tunnel,

$$m = 191{\cdot}3\, A_t \left(\frac{p_D}{p_0} \right)^{\frac{2}{7}} \left(\frac{288}{T_D} \right)^{\frac{1}{2}} \left\{ 1 - \left(\frac{p_0}{p_D} \right)^{\frac{2}{7}} \right\}^{\frac{1}{2}} \text{ lb./sec.} \quad (6)$$

Equations (4) and (6) give the same values of m when

e.g. Luftfahrtforschung, Vol. 14, p. 564 (1937).

*This is reasonable except when the difference between the blowing pressure p_D and the free-stream pressure p_0 is so small that it is of the same order as the difference between p_0 and the local surface pressure on the model close to the nozzle exit.

the flow in the nozzle is just sonic, and $\frac{p_0}{p_D} = 0{\cdot}5283$.

Finally, from equations (1), (2) and (6)

$$C_\mu = \frac{1{\cdot}483 \times 10^4}{\frac{1}{2}\rho_0 V_0^2 S} \cdot A_t \cdot \left\{ \left(\frac{p_D}{p_0}\right)^{\frac{2}{7}} - 1 \right\} \quad . \qquad (7)$$

being independent of duct temperature, as before.

NOTES ON ACCURACY OF MEASUREMENT

(*i*) If C_μ is derived via equation (3), m is measured separately. Assuming m is obtained from a Pitot-static traverse or orifice plate or similar device,

$$m \propto (\Delta h)^{\frac{1}{2}} \cdot (p_m)^{\frac{1}{2}} \cdot \frac{1}{(T_m)^{\frac{1}{2}}}$$

where suffix m refers to the conditions at the measuring point.

Hence from equation (3)

$$C_\mu \propto (\Delta h)^{\frac{1}{2}} (p_m)^{\frac{1}{2}} \left(\frac{T_D}{T_m}\right)^{\frac{1}{2}} \left\{ 1 - \left(\frac{p_0}{p_D}\right)^{\frac{2}{7}} \right\}^{\frac{1}{2}} .$$

Thus 1 per cent error in measuring Δh on a manometer causes $\frac{1}{2}$ per cent error in C_μ. Also, 1 per cent on air temperature T_D in the model or T_m at the orifice plate (measured in degrees Absolute) implies $\frac{1}{2}$ per cent on C_μ. As discussed under Case A, T_D and T_m are often within a few degrees of one another and cancel out to the required accuracy.

Since the static pressure p_m at the orifice plate is closely related to the model duct pressure p_D, it follows that the variation of C_μ with the pressure applied to the system is given by

$$C_\mu \propto (p_D)^{\frac{1}{2}} \left\{ 1 - \left(\frac{p_0}{p_D}\right)^{\frac{2}{7}} \right\}^{\frac{1}{2}} .$$

The accuracy in C_μ resulting from variations in p_D is obtained by logarithmic differentiation,

$$\frac{dC_\mu}{C_\mu} = \frac{1}{2} \frac{1 - \frac{5}{7}\left(\frac{p_0}{p_D}\right)^{\frac{2}{7}}}{1 - \left(\frac{p_0}{p_D}\right)^{\frac{2}{7}}} \cdot \frac{dp_D}{p_D}$$

For example, control to 0·5 in. of mercury at a 2:1 pressure ratio in an atmospheric wind tunnel ($p_0 = 30$ in. mercury) is equivalent to 0·8 per cent in pressure, and results in just under 1 per cent variation in C_μ.

It should be noted that, in this method of measuring C_μ, the value of the nozzle area A_t is not required, and the control of the width of the nozzle need only be considered in relation to the required spanwise distribution of C_μ.

(*ii*) If m, as well as v_j, is calculated on the assumption of isentropic expansion, no measurement of temperature need be made in the evaluation of C_μ. For the supersonic jet, equation (5) yields

$$\frac{dC_\mu}{C_\mu} = \frac{1 - \frac{6}{7}\left(\frac{p_0}{p_D}\right)^{\frac{2}{7}}}{1 - \left(\frac{p_0}{p_D}\right)^{\frac{2}{7}}} \cdot \frac{dp_D}{p_D} .$$

For example, in an atmospheric wind tunnel, control to 0·5 in. mercury at a 2:1 pressure ratio (0·8 per cent on p_D) corresponds to 1·3 per cent on C_μ. Also 1 in. mercury at 4:1, the same percentage of p_D, gives 1 per cent on C_μ.

For the subsonic jet, equation (7) gives

$$\frac{dC_\mu}{C_\mu} = \frac{2}{7} \frac{1}{1 - \left(\frac{p_0}{p_D}\right)^{\frac{2}{7}}} \cdot \frac{dp_D}{p_D} .$$

Thus, control to 0·15 in. mercury at a 1·5:1 pressure ratio in an atmospheric tunnel means 0·35 per cent on p_D and 1 per cent on C_μ. For lower pressure ratios the calculation of mass flow from equation (6) becomes more difficult to perform accurately, with a corresponding effect on the accuracy of C_μ. For example, at a 1·2:1 pressure ratio, control to 0·1 in. mercury (0·28 per cent of p_D) leads to 1·6 per cent variation in C_μ.

This method of measuring C_μ by theoretical evaluation of the mass flow, depends largely, for its reliability, on the accurate evaluation of the nozzle area A_t in equations (5) and (7). Even if the nozzle gap is measured with feeler gauges while blowing is being applied, so that temperature and pressure distortions of the nozzle plates on the model are allowed for, it will not be possible in many cases to evaluate the geometric area to better than 5 per cent. Also in practice, the effective area A_t may be a little less than the full geometric value because of boundary layers, wakes or over-contraction of the flow in the nozzle.

*The Fourth Barnwell Memorial Lecture**

A Specification for Engineering Education

by

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1. The Need for Engineers and Engineering

So much has been said in the past four or five years of the need for Great Britain to increase the numbers of her trained scientists and engineers, and so much emphasis has been put on training by industry, that the country as a whole is aware, if somewhat vaguely, of the urgency of the present national need. Whether there is a real awareness of the continuing nature of the need, is, however, far less certain; and I make this my apologia for attempting some further discussion of a position which, to engineers at least, is at present patently and painfully obvious. It must be remembered that only a few short years ago, engineering skill was at a discount and the engineer something of a social pariah; moreover, the higher his academic training, the further he was beyond the pale. It was said of many a man that he held his job not because he had a degree in engineering, but in spite of it.

The pendulum has now swung far in the other direction, and the trained engineer is very much at a premium. In the University of Bristol—and our experience is typical—we have during the Easter term, on every day except Saturdays and Sundays, at least two, frequently three, and sometimes four deputations of people from industrial and allied organisations; these people, through the agency of the Appointments Board, attempt—or perhaps tempt is the right word—to recruit those who will graduate during the year. I do not regard this as a healthy situation: when a young man graduates, his job should be a challenge rather than a gift; but it does indicate the importance attached by industry to the recruitment of trained men. The pendulum has certainly swung; but since a pendulum has an ingrained habit of reversing its swing, it is, I think, well worth while to try to show that there is, and will always be, a need for engineering in a progressive democratic country.

A penetrating and exceedingly interesting analysis of this question was given last year, in the Second Graham Clark Lecture, by Sir Maurice Bowra, Warden of Wadham College, Oxford. Here was a very distinguished humanist and man of letters looking objectively at engineering in its impact on society. Bowra claimed that man differs from the beasts, not as Beaumarchais said in drinking when not thirsty and making love all the year round, but mainly in being able to turn nature to his own use. He thus, in effect, picks on engineering ability as the prime distinguishing feature. Many would no doubt challenge this; but at least it is easy to remark that the arts, for example, could not have flourished without the aid of those who devised the instruments for writing, printing, painting, and making music. In developing his theme, Bowra pointed to the decay of the early civilisations—Egyptian, Chinese, and Greco-Roman—and stated categorically that they perished because the ruling classes, in their attitude to engineering, were snobs.

He quotes, for example, Plutarch on the subject of the mechanical inventions of Archimedes:

> "Though these inventions had obtained for him the renown of more than human sagacity, he yet would not deign to leave behind him any written work on such subjects; but regarding as sordid and ignoble the business of mechanics and every sort of art which is directed to use and profit, he placed his whole ambition in those speculations, the beauty and subtlety of which is untainted by any admixture of the common needs of life."

Here is clearly the beginning of the notion that abstract science is pure, and that, *per contra*, applied science is therefore impure. As one who was trained in the abstract sciences, I say plainly that this is a pernicious doctrine, as much now as it was in the time of Archimedes. It was, however, typical of the attitude not only of Archimedes but of all his fellows. In their time there was an almost inexhaustible supply of human slave labour, and this fact closed their minds to the desirability of executing any task by other and more efficient means. A man's stature was assessed by the number of his slaves rather than by any mechanical yardstick; thus wealth and importance were inconsistent with any notions for achieving results by other than slave labour methods. They did not recognise that mental and spiritual development marches hand-in-hand with material advances; in the latter, and then in the former, they became static and complacent, and in the end had no defences against the races that earlier

*Given to the Bristol Branch of the Society on 13th March 1957.

they had plundered and enslaved. If I may again quote Bowra:

> "The trouble with a society which does not believe in engineering or see its possibilities is not that it cannot be civilised, but that it is not likely to survive."

It has taken nearly 20 centuries for this conclusion to be appreciated, and then not fully: even since the beginning of what has been called the Scientific Revolution the climate of opinion has varied greatly*. A hundred and fifty years ago the great engineering scientists of the period were honoured men. But, while the industries founded on their work brought wealth and social status to many, there grew up also a tendency to despise and ignore the agency by which these benefits had accrued; and the status and importance of the engineer declined. Now, once again, the economic stress of the present day has caused a new realisation of the urgent need we have of developing our engineering instincts and skills.

A word on the place of engineering in the present economic position of Great Britain may not be out of place here. Col. B. H. Leeson, in a recent lecture before the Institution of Electrical Engineers, gave some impressive figures on this subject. In the years immediately before the Second World War the value of engineering exports from this country was only about 11 per cent of the whole, with coal, textiles, and chemical products accounting for about 50 per cent. By 1952 the total value of exports had increased by a factor of four or five, and of this increased total engineering exports had risen to 42 per cent, or if iron and steel are included, to 53 per cent of the whole; the value of coal and textile products had shrunk relatively to insignificance. These are isolated figures, but I do not need to labour or reinforce them. The economic history of the world at present is largely one of engineering effort. In Russia and in China, where the depressed peasantry of 50 years ago paralleled the slave labour of the Roman empire, immense efforts are being made to improve the standard of living through the development of engineering; and in America, the stature of the U.S.A., although founded on an abundance of natural resources, has been built up by an almost unvarying obedience to the principle that efficient machinery matters above almost all else.

Perhaps I may summarise by quoting another humanist, Mr. Alec Peterson, Headmaster of Dover College. In a broadcast last year, "Tradition faces the challenge," Peterson stated the position I have attempted to outline with pith and point:

> "If we are to prosper in the sense of raising our standard of living—if perhaps we are to survive at all—we must rely, not on our natural resources (which are now matched all over the world), not on our overseas investments (which are now gone), not on our accumulated capital equipment (which is now largely out of date), but on our productive and our industrial skill . . . . We must live by our wits and the sweat of our brows. And that means the wits of trained scientists and technicians . . . . it is a problem of education."

The essence of the matter is in this last sentence, which I would now like to examine in more detail.

2. The Need for Increased Education in Engineering

I have tried to state and explain the national need for engineers; it is, I think, a necessary preamble to my main theme, that of education. I make no apology for the preamble: all true history is knowledge, just as all knowledge, once established, becomes a part of history; and a man who is equipped with some knowledge of the happenings of the past may often thereby avoid the pitfalls of the present and future. Here the lesson is that we need engineers and that in consequence we need to educate more engineers better. Professor Mucklow has said:

> "Britain must increasingly depend for her well-being on an expanding level of exports of engineering products of all kinds . . . . better craftsmanship, improved methods of production, more advanced design, and greater imagination and initiative in the application of scientific thought and discovery. The matter therefore resolves itself essentially to one of education and training . . . ."

Here there is a shortage. We have an educational system geared to the needs—and the prejudices—of the past; and we must expand it greatly to meet the demands of the future. We shall no doubt suffer severe growing pains in the process, and shall make many mistakes, but the challenge and the necessity for action are unavoidable. The *Financial Times*, in its articles on "The Bottleneck in Science" states that the situation has been allowed to deteriorate very seriously, so that the proportion of scientists and engineers in the working population of this country is only half of that in America. And even in America, developments in automation—a philosophy which had its birth there—are being slowed down by the scarcity of trained men with creative imagination. As regards Russia, the continued efforts to develop the technological resources of the country are exemplified by the plans to train four million engineers and their technical assistants and craftsmen in five years.

These are sobering figures, and call for a careful and rational assessment of what we have been doing, and what we require to do in the next decade or two. A useful index here is the number of graduates—or the equivalent—produced annually in various countries.

Sir Winston Churchill, speaking on this subject a year or so ago, gave the annual output of engineering graduates in Russia, America, and Britain as 50,000, 25,000 and 1,800 respectively. But while these figures may be formally accurate, they would, if giving a complete picture, be very depressing, and would suggest that our task is impossible. However, I think myself that the comparison falls down on the interpretation of the word "graduate." For example, in America child

*See also *The Organisation of Science in England* by D. S. L. Cardwell; Heinemann, 1957.

education begins two years later than it does in Great Britain, and this two year gap persists throughout the educational curriculum right up to the point of graduation. Those leaving school in this country are two years further up the educational ladder than those moving from high school to college in America, and those leaving universities here with a first degree are, by and large, two years farther advanced than the graduate of American colleges and universities.

This statement is based on my own experience, which is admittedly limited. But graduates from my own Department have been to the U.S.A. with post-graduate fellowships (from, for example, the English-Speaking Union) tenable at institutions such as the California Institute of Technology, the Massachusetts Institute of Technology, and the University of Illinois; and in each case they have been assigned to the third year of the post-graduate courses. Conversely, we had last year a graduate from a university of the U.S.A. who came to the Faculty of Engineering at Bristol. We placed him in our second undergraduate year; he did very well, although finding our standard of mathematics rather testing. Other universities have, I know, had the same experience.

I am not, of course, intending any slur on education in America. They carry their post-graduate courses to levels quite as high as our own, and a Ph.D. degree from a reputable American university is a mark of high attainment, fully comparable with a British Ph.D. But their post-graduate courses are necessarily longer and contain more formal instruction than is the case in Britain, for the simple reason that they attach the label "graduate" at an earlier stage.

Comparisons are always odious and are frequently invalidated by lack of compatibility of the data involved. It seems to be clear, however, that a fairer comparison than that based on graduates from universities only, would result if the numbers of those trained in technical colleges to the level of the Higher National Certificate (and certainly the Higher National Diploma) are included on the British side. The number of such certificates awarded annually is about 9,500, bringing the British total to over 11,000 annually. The *per capita* totals for Russia, America, and Britain are then not unreasonably different. More than this it is difficult to say, since the borderline between science and engineering is vague and indefinite. If one takes the broad field of science and engineering as a whole, and especially if one includes the numbers of technical assistants, it seems certain that Great Britain is lagging in the race and has a good deal of ground to make up.

3. History of the Growth of Engineering Education

I would like here to cast a second short backward glance at history: this time at the history of the development of engineering education, especially in Great Britain and on the Continent. We may thus find out why the differences in approach have come about. I do this, in part at least, because there is a body of opinion in this country—I am glad to say it is less vocal now than it was three or four years ago—which holds that we should copy the Continent and the U.S.A. by developing universities of technology alone; and that in the process engineering should be wholly abstracted as a discipline from existing universities. This view seems to be based on the philosophy that the other fellow is necessarily right: but I do not subscribe to it myself. I think the British system contains the seeds which, given proper conditions for germination, can re-establish British engineering in the flowering and pre-eminent position it held a century ago.

It appears that two factors were mainly responsible for dictating the development on the Continent of high quality specialist schools of engineering.* The first and most important was military necessity. Wars on the Continent called for high mobility of the forces employed, and demanded in consequence a high standard of roads and bridges; the Romans had set the example for this centuries before. As a result of this requirement in France, engineering science began to be taught in the military schools founded about 1720, and a treatise on the "Science des Ingénieurs" was published in 1729. For the body equivalent to our Royal Engineers —the Corps des Ponts et Chaussées—an Ecole des Ponts et Chaussées was founded in 1747. It is particularly to be observed that the engineers trained in these schools were of officer status. In 1794, during the period of the French Revolution, and possibly as an outcome of it, the Ecole Politechnique de Paris was founded; and this set the pattern for polytechnic institutes on the Continent. The second factor in this trend of development was the attitude of the universities on the Continent. At the time, they were concerned only with the humanities, and were unwilling to find a place for science and especially, those aspects of science which, at the time, were largely concerned with military activity.

In Russia, the same general pattern seems to have been followed. As early as 1586 a Russian engineer constructed a cannon weighing 40 tons and having a bore of 89 mm. and a length of over 5 metres; it is preserved in Moscow to the present day. The requirement for trained engineers for military purposes caused Peter the Great to set up a Civil Service of engineers with a rank pattern equivalent to that of the military services. Thus the engineers both on the supply side and on the military side were of officer class. For training purposes, a succession of schools was rapidly developed: a Naval Academy (1715), Engineer School (1719), and Artillery School (1722). The St. Petersburg Academy of Science was founded in 1725, schools of hydraulic engineering in 1767 and 1768, and a school of mines in 1773. Finally, in 1809 a school for training in engineering communications was set up, and in 1830 the Moscow Higher Technical Institute—which still flourishes under the name of the Baumann Institute—was founded.

*I am largely indebted to B. L. Goodlet for the historical notes which follow; *see*, for instance, *The Engineer*, 15th February 1957.

Developments in the New World came much later, of course; and insofar as North America has built a Continental system on to one which was fundamentally British, the influence of distinguished immigrants from Continental countries may be presumed to have played no small part. The views of men of the calibre of Einstein, von Kármán and Timoshenko must have been influential in this development.

In Great Britain the situation was different. Here we cradled craft engineering, relatively uninfluenced by the dictates of military necessity, since the last foreign military invasion was in 1066. Except in the naval sphere, we had no urgent requirement for works of a military category—a fact which, incidentally, probably accounts for the quite startling differences in the attitude of British and Continental governments even at the present time to the building of trunk roads: on the Continent today, small countries and poor countries think it expedient to lay down hundreds of miles of autobahnen and autostrada, while Great Britain havers for years about a few miles of by-pass road and fails to find justification for a Severn bridge at Aust. Military considerations therefore did not press as urgently here as on the Continent for the training of specialist engineers; in addition, abstract science was not shunned by the universities here. This fact probably stemmed, in part at least, from the world-wide reputation of Isaac Newton (who in 1669 was appointed Lucasian Professor of Mathematics in the University of Cambridge) and from the increasing prestige of the Royal Society. Taken together, these circumstances lessened or obviated any need for specialist engineering institutions such as were taking shape on the Continent, and in Britain academic engineering science on the one hand and craft engineering on the other, grew up side by side; the craft engineering was fostered, nurtured, and passed on by the apprentice system developed by the guilds of craftsmen. Out of this system grew the developments of the Industrial Revolution: here the engineering craftsmen, now known as mechanics, began to feel the need for a grafting on to their skill of some buds of academic knowledge; and mechanics' institutes, trade schools, and the like—the forerunners of technical colleges—began to appear. To these were added—although in smaller numbers—the polytechnics, such as the Polytechnic Institution in Regent Street, London, founded by the distinguished engineer and prophet of aeronautics, Sir George Cayley.

The pattern which has developed is perhaps best illustrated by the apprentice schools of the large engineering organisations, and particularly of the electrical and aircraft firms. The majority are craft apprentices: the men who will become the skilled mechanics with a fund of knowledge represented by, say, the Ordinary National Certificate; most of the remainder are engineering apprentices, who will obtain a professional qualification through the avenue of the Higher National Certificate or Diploma, and who will be the designers, draughtsmen, and production engineers; and finally the undergraduate apprentices, who will proceed to a university to obtain a degree, and who—by and large—will become the project engineers, research workers, and "back-room boys." To this last class must be added the men who move to engineering and industry from courses in abstract science and mathematics: a group which has a significant contribution to make.

4. Some Comparisons

Having looked at the origins of engineering education in their various nurseries, we must now examine present methods, as a desirable and indeed necessary preliminary to thinking of developments in the British system.

Broadly speaking, the two extremes are provided by the intensive specialist institutions at present existing in Russia and the diverse methods of Great Britain. In between are the Technical High Schools of the Continent—nearer the Russian system—and the American system with a few large specialist organisations, which is more closely allied to our own.

I have referred earlier to the foundation of the Moscow Higher Technical Institute. Now the Baumann Institute, this is a monotechnic; it is built on a university pattern, but trains mechanical engineers only. There are six faculties: Thermal and Hydraulic Machines, Machine Construction, Precision Instruments, Transport Machines, Mechanical Technology, and Metal Technology; and there is an average of five Chairs per faculy. The course lasts for 5½ years and is heavily didactic; much attention is given to drawing and design and a good deal (in the earlier years) to fundamental science: but the aim is to produce a specialist. As Goodlet has said, the object of such institutes appears to be to teach everyone to be useful and to let who will be clever afterwards. The philosophy and method are far removed from those of this country: but it must be remembered that the curricula of the schools are almost universally orientated towards industrial science and engineering, for the understandable reason that no one stands higher in the Russian social scale, or is better paid, than the professional engineer. This status extends even beyond the engineer to his machines. If I may quote Goodlet again*:

> "Wealth is produced by means of machines, which therefore occupy a special position of honour in Communist philosophy. The machine which produces wealth and lightens human toil, the machine tool which produces the machines, the prime mover which supplies power, ... these are the pillars of the Communist system."

To Western ears this sounds impossibly materialistic, and I am told that in the past year or so Russia has herself concluded that some attention to the humanities would provide a desirable leaven to her specialist courses.

At the technical assistant and craftsman level the picture is similar. The former is trained in a "technicum" or in a night school; the technicum gives a full-time three year course. The craftsman is usually

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given an intensive course for a year or so in a trade school attached to a works. It has to be remembered that Russia is recruiting her industrial material from an erstwhile peasantry and there is no tradition of guilds of craftsmen and apprenticeship such as we know.

Let us now turn to the other extreme, the British method, and begin with the craftsmen. These are still trained mainly by the time-honoured apprentice system. In many large organisations, apprentice schools with some formalised training are in being, but the great majority of industry still relies on the passing-on of knowledge and skill from one generation to the next. Formal teaching at the hands of trained instructors is still largely to come.

At the middle level we train our technical assistants largely through part-time day release classes in technical colleges; if they proceed to corporate membership of a professional Institution it is, at the end, frequently achieved by voluntary evening work. Some full-time and many more part-time "sandwich" courses are becoming available, but the number of people who can take advantage of these is relatively few.

At the university level, the philosophy of training is very far removed from that of the opposite number in Russia. Instruction is given in engineering science rather than engineering itself, and the emphasis is always on training the mind rather than on inculcating a knowledge of specific methods and formulae. The university teacher is far better pleased if his student objects to the established method or idea on the ground that he thinks he can provide a better (even though, in the event, he can't) than if the student shows an excellent knowledge but slavish acceptance of it. And educationalists are frequently being adjured not to forget this mind-training as the vital thing. H. D. Morgan, a civil engineer, recently wrote:

> "Specialisation is on the increase and the demand for scientific and technical manpower is so great that the mind-training aspects of education are tending to be forgotten . . . . There is a need for individuals who can think on broad lines, and to supply this it is by no means certain that the technical training favoured today is comparable with the classical education of yesterday."

So long as engineering faculties remain in universities, I do not think this vital but intangible quality of teaching will be lost. The student, no less than the teacher, will be for much of his time in contact with those of, or intended for, the medical or legal professions, with classical scholars, historians, or scientists. But this is a digression.

In addition to universities, there are a few colleges of special character which graft an engineering training of university character on to stems of other origins: here I am thinking particularly of the College of Aeronautics, which gives a two-year residential course: the students may be holders of Higher National Certificates, when the method and outlook of their new studies is probably less familiar than the material, or holders of university degrees in, say Mathematics or Physics, when the material is new but the method familiar. Another source of students is provided by engineers from the fighting Services.

But by and large the object of training is *not* to produce individuals immediately useful to industry: it is to produce men with a broad background of related knowledge who will critically examine the methods of industry when they are first introduced to them as graduate trainees.

History suggests that the British system has much to commend it, at least for a substantial part of the job in hand; for it is certainly true that over the past two or three centuries, Britain has led the world in the field of engineering design and the development of new ideas. One has only to cite such things as shipbuilding, railway engineering, the gas turbine, and industrial nuclear engineering to support this view; and it is gratifying to realise that, on the technological level in the Aircraft Industry, for example, we can still hold our own with the United States despite the enormously greater deployment of effort in that country. On the other hand, it is undoubtedly true that there are aspects of engineering—perhaps production is the most notable example—in which Britain seriously lags, and for which we require a new outlook.

Before discussing possible changes, however, it is clearly pertinent to examine possible sources of supply of the increased numbers of students for whom new courses will—we hope—be a real attraction.

5. Sources of Supply of Students

The numbers of engineers trained at all levels which will be required for industry in the next decade or so have been variously estimated as an increase of from 50 to over 100 per cent of the numbers trained at present. We must therefore enquire: where will this greatly increased body of trainees come from?

Nature has, in part, supplied the answer; in 1966 the number of eighteen-year-olds will be some 45 per cent higher than it is now. The post-war "bulge" in the birth rate has certainly provided much human material that will then be crying out for training. Clearly the country must endeavour to encourage a greater proportion of these youngsters to enter engineering at all levels, since it is in engineering that the need is greatest.

As regards training at the engineering and undergraduate apprentice levels in the more immediate future, we may look for some turnover towards engineering from both the arts and the science sides at schools. As regards the turnover from arts, Peterson, speaking of the choice confronting pupils, says

> "If a boy is at all clever he usually has to make it before he is fifteen . . . . there are still traces of a bias towards the arts side—I feel sure of this myself, whatever people may say to the contrary,"

and he continues by advancing four cogent and convincing reasons why this is so. Perhaps a larger turnover, however, might result from those aiming at studying abstract science; a greater knowledge in schools of the importance and nature of engineering would greatly help here—it is unfortunate that trained

engineers so seldom exert influence directly on schools and their masters. There is, I fear, a great tendency for science masters to dignify, and indeed almost to deify, the word " research " to their pupils, who go off to places of further instruction imagining themselves as budding Rutherfords. An excellent ambition, but given to very few to achieve; and many so directed are, I fear, misdirected. Do not imagine that I am suggesting that students not good enough to achieve the best in physics are good enough for engineering; I know from my own experience that the discipline of engineering is fully as testing as that of the abstract sciences. But since many of the disappointed embryo Rutherfords have, in fact, a better appreciation of classical physics and mechanics than of modern atomic physics, and since they do, in the end, turn to industry for employment, it seems that some, at least, could better be trained as engineers from the beginning, rather than having to pick it up in industry. But not all should change, as I shall show later.

We might also step up the numbers of our engineers by universal attention to the formal training of craft apprentices. In many firms, especially the smaller ones, the training is distinctly adventitious in character. Systematic training might well bring to light many a man for whom, in present circumstances, the opportunity to show his qualities does not exist; such at least, seems to be the lesson to be drawn from the experience of those firms which do take their apprentice training seriously. For myself, I would like to see this training carried out more fully on the " sandwich " basis, with periods in the works alternating with periods in the apprentice school or training college.

The training of girls offers a further source of supply; as has been said, it is a source which Russia is using very fully. The White Paper on Technical Education, published a year ago (H.M.S.O., Cmd. 9703), has some useful comments to offer here; it remarks particularly on the feeling, frequently expressed, that there is not much point in further education for girls since they will probably marry and so waste their training. This can at once be countered by the statement that half the women in Britain between the ages of 15 and 35 are " gainfully occupied." Even a small proportion of these, trained and recruited to the engineering industry, would be immensely helpful. And it is, I am certain, the firm belief of all sensible people that such training is not wasted when a girl marries; as the White Paper says, it will help her " to build her own family on foundations of common interests and understanding." Whether we agree with their methods or not, the Russians are at least realists; and it is the fact that in Russia three-quarters of the doctors and one-quarter of the engineers are women.

Finally, it is an important fact that in the past few years the number of seventeen-year-olds in schools has been increasing annually by five per cent. This trend towards staying longer at school should provide an increasing source of valuable recruits.

On the whole, then, we may conclude that the recruits required by the engineering industry may be found if the authorities concerned are guided by common sense, good will, and a sense of urgency.

6. The General Specification

From what I have said it will be clear that my own personal view is that the British system is basically sound and that we should lōse, rather than gain, from the introduction in this country of Continental or American methods in place of our own. But this is not to say that all is perfect. By no means: we have clearly got to adopt quite a number of methods and ideas from other countries. It is my view, however, that we need to build up our own system with these ideas, rather than to abstract anything from it.

The White Paper on Technical Education emphasises these views. It quotes the Bradford Speech of Sir Anthony Eden (then Prime Minister) on the Scientific Revolution:

> " The prizes will not go to the countries with the largest population. Those with the best systems of education will win. Science and technical skill give a dozen men the power to do as much as thousands did fifty years ago. Our scientists are doing brilliant work. But if we are to make full use of what we are learning, we shall need many more scientists, engineers, and technicians. I am determined that this shortage shall be made good."

Some comments follow, in the Introduction to the White Paper, on the necessary qualities of broadness of outlook to which I have already made reference. For example:

> " Technical education must not be too narrowly vocational or too confined to one skill or trade. Swift change is the characteristic of our age, so that a main purpose of the technical education of the future must be to teach boys and girls to be adaptable. Versatility has been the aim of a classical education; technical studies should lead to a similar versatility, and should therefore be firmly grounded on the fundamentals of mathematics and science ... More attention will have to be given to the teaching of good plain English, the use of which saves time and money and avoids trouble . . . Moreover, a place must always be found in technical studies for liberal education . . . . We cannot afford to fall behind in technical accomplishments or to neglect spiritual and human values."

This general approach is in direct contrast to the Russian system (and even more to the present Chinese methods), where as I have noted earlier we are told that even in schools the curricula are biased towards industrial science and engineering, and in which the humanities are, relatively, regarded as effete and obsolete. Nevertheless, the British point of view finds favour with most people, whether academic or not. The *Financial Times* (which has, one presumes, an eye to the material side of things) says

> " At the moment there is a tendency to get the worst of both worlds in the provision of premature specialisation combined with an absence of trained

technologists. There is no fundamental reason why, with judicious pruning of syllabuses, education up to university level should not consist of a broad training in science in addition to the humanities ."

Alec Peterson, from whom I have already quoted, expresses the same viewpoint and the same conviction:

"Our aim, educationally, is to train people in reasoning—true enough; but we have to accept the fact that the problems about which the new generation must be able to reason are increasingly problems of the scientific type. As long as the problems which the average Englishman had to tackle were mainly political, legal, or administrative, he did not necessarily have to have any understanding of science. Now that we are living on our wits and on our sweat, it is often essential. But I do not believe that this new situation means that we must throw overboard the whole of our traditional humanist education. No; we should enrich it rather by taking on board more science."

Let us now examine in more detail some of the objectives which are desirable, and indeed essential, if we are to meet this general specification.

6.1. FLEXIBILITY

The White Paper on Technical Education states:

"The British system of technical education is probably more flexible than any other. For example, in most other countries it is very unusual for anyone leaving school before the age of eighteen to be able to embark on a career leading to the highest technological qualifications."

It should be a cardinal point of our future policy that this flexibility shall be maintained. This means that we must keep our present avenues of training and the various goals at which students may aim, although the methods and standards will, of course, vary with time and experience. In particular, I think it important that we should keep the system which admits those trained in abstract science and mathematics to the engineering profession. If I may use aeronautical engineering as an illustration, I would point to the enormously rapid advances made in this profession which have influenced civil engineering (through new ideas in structures), mechanical engineering (through power plant development), and electrical engineering (through its special requirements in light current equipment), and which, in the short space of fifty years since the first powered flight, is far more nearly able to "put a girdle round about the earth in forty minutes" than any other branch could even contemplate. And I believe these advances are due in no small measure to the welcome given by the aeronautical engineering industry to theoretical physicists and mathematicians, as well as to engineers.

Mathematics does perhaps deserve a special mention. It has been truly said that whereas Latin was the universal language of 300 years ago, mathematics is the universal language of today. A little consideration will show that this aphorism is very true. Mathematics is at base a discipline employing a shorthand notation for describing a series of logical steps; and as such it is becoming a necessity in all branches of human knowledge. It has always been a possible part of a humanist course: I suggest that it is now an essential part.

6.2. LIBERAL STUDIES

Under this wide and rather vague heading appear a great many things with which it is desirable that the engineer should have more than a nodding acquaintance. In his technical studies the engineering student joins hands on the one side with the abstract scientist; he must also join hands on the other side with the humanist, in some at least of his activities, if he is to apply successfully the findings of science to the use of humanity. Moreover, it will not be sufficient merely to add courses of a humanist type to technical courses: integration is of vital importance. It should be shown how the engineer is concerned with the mental and moral life of man; he must be made aware of the scientific origins of engineering and of its human ends.

6.2.1. *Economics*

I write with great diffidence here, since economics is a subject of which I am totally ignorant. Nevertheless, I am sure that the technically trained engineer would benefit enormously from additional training, even though it be only elementary, in such subjects as business management, accountancy, costing, and the organisation of industry. Technical training can show why a machine can be of use to humanity: but it is necessary also that there should be training to show how the machine can be made to work efficiently for humanity. And if, in particular, it is to work efficiently to the advantage of that particular section of humanity which is British, then a knowledge of our finance and exchange systems, and of trading and commercial skills, is clearly essential.

May I add here that in the University of Bristol, students in the Engineering Faculty are required, as part of the degree curriculum, to take courses and examinations in Economics within the Faculty of Arts.

6.2.2. *Language and Letters*

Most adolescents have some knowledge of a foreign language, and clearly, if time permitted, further attention here would be desirable. However, the increasing knowledge of the English language shown by other nations (it is, for example, the international language for air travel) is modifying this necessity. But if it does this, it accentuates the need for a good working knowledge of English for British students. It is unfortunately a fact of common experience that students of science and engineering can be painfully inarticulate, especially in the written word. Prolixity, circumlocution, bad grammar, and ambiguity are very common faults; and it is quite remarkable how few people realise that a piece of mathematical analysis is only a shorthand form of a logical statement: that, for example, the equation sign is a verb: and that the whole should be

constructed and punctuated just as if it were a piece of prose writing.

Here again I am preaching what we practise in the University of Bristol: our students have, in their last year, to take a course and examination in English in order to qualify for a degree in Engineering. It is a special course which the Department of English provides for us: grammar and literature are incidental to it, since it is a course in the use of the English language, and its object is to teach students to express their ideas lucidly, directly, and unambiguously. Nearly all students say they have found the course interesting and helpful.

6.2.3. *History*

I have earlier stated my conviction as to the importance of history, and especially of the history of one's own subject; I shall not labour the point further here.

6.2.4. *Industrial Psychology*

This subject invites cheap moralisation on industrial strife, which I must be careful to avoid. It is, however, arguable that much of our industrial trouble today could have been avoided, or at least lessened, if there had been a wider knowledge of psychology and human relationships in industry. Much has been done, much has recently been learned in this comparatively new branch of the humanities; and as the engineer learns the way to use machines, so, logically, he should study the reactions of those who operate the machines.

6.3. PRODUCTION ENGINEERING

It has always appeared to me that the principal failing of British engineering, in a comparison with other countries, is our relative inability to translate our ideas—which are excellent—into practical designs and thence into hardware; or at least, our inability to capitalise our ideas in the short time which would be required by, say, American engineers. This is perhaps a personal hobby-horse, which I must ride warily; and in doing so, I shall lean on the words of others. B. V. Bowden, writing in the *Manchester Guardian*, says

> "Although almost all undergraduate engineers in this country study the principles of mechanical design and the theory of structures, ... Very few undergraduate engineers are taught anything about production technology; and during their courses in structural engineering the students rarely or never concern themselves with the economic and technological problems of manufacturing the structures . . . . nor do they become familiar with the scientific principles underlying the design of the tools or equipment that are used in production. How, therefore, can they design things which can be produced efficiently?"

and later

> "More than six thousand students took degree courses in production engineering in the United States last year; . . . . There were only 44 people throughout England taking degree and Higher National Diploma and "sandwich" courses in production engineering . . . . Delft had as many as the whole of this country. In America 1,610 students were taking postgraduate diplomas . . . . there were only 52 in England."

Similarly, B. L. Goodlet, in his comparisons between Russian and British methods of training, draws attention to the specialist treatment accorded to various phases of manufacturing processes. He says of the Russian graduate engineer:

> "I am certain that he gets a better grounding in engineering drawing, design, and manufacturing technology . . . . than our men."

For myself, I am unable to argue a case from practical experience, but I feel sure economic considerations will before long ensure that Great Britain pays more attention to this aspect of engineering training than has hitherto been the case. I do not, however, think this should be a discipline substituted for one of our recognised subjects; it must be added on, and at a stage when the student has had a sufficient experience of industry to appreciate its meaning. The Institution of Production Engineers has recently issued a report on a Conference held last year in Holland; it is entitled "The Teaching of Production Engineering at University Level," and it recommends that after a full year of training in industrial workshops and an academic course of three years with some bias toward the principles of production, a student should spend a full year devoted to the special subjects of production engineering.

I do not myself think it necessary to bias an undergraduate course, but do think that a formal postgraduate training has much to commend it. I have had discussions with colleagues on this subject, and it has been suggested that formal training is superfluous, since production engineering and allied subjects really represent the operation of simple common sense. But another colleague thought that much could be said for postgraduate courses in common sense! It is to be feared, also, that not all engineers, even those who are brilliant, can be regarded as applying that useful household commodity to all phases of their thinking.

I have spoken of undergraduate courses; but training is necessary also for craft apprentices, and most particularly for engineering apprentices, since it is from their ranks that most of the production designers and manufacturers are likely to come. Here I would like to mention what is a hope of my own; it concerns the Diploma in Technology, awarded by the National Council for Technological Awards—the "Hives Council." It is intended that this award shall have the standard of an Honours degree from a university, and it is true that the conditions under which it will be earned by students have much in common with university disciplines. But since it must clearly be complementary to, and not competitive with, a university award, it should have some signal point of difference; and I think myself that there is an excellent opportunity here to make the Dip. Tech. award connote

training in the methods and principles of production engineering. (I am bound to add here, since I am a member of the National Council, that this is my own personal view and hope, and must not be taken as an expression of the Council's views). There must be, in a training for an award having the standard of a university degree, some introduction to research activities; and the problems of production engineering offer this possibility. Bowden instances a number of topics, such as the study of ceramic tools for high speed cutting processes, and adds:

> "It is absurd to say that research in such subjects is any less difficult, any less rewarding, or any less stimulating than research in pure science."

7. Methods for Meeting the Specification

To begin with, we revert to the question of flexibility; and for this, in general, we must retain the variety of avenues of training and of qualifications for which students may work. The principal qualifications are, I suppose, the Ordinary National Certificate, Higher National Certificate and Higher National Diploma, Diploma in Technology, and university degree. As regards the Ordinary National Certificate, I am myself a proponent of the idea that this should be a basic qualification for all engineers without reference to their speciality, so that an Ordinary National Certificate in Engineering could be a starting point for further study in, for example, mechanical or electrical engineering.

The really vital thing, however we may arrange the detail, is, of course, to ensure that the training given is regarded as a privilege and accepted as a challenge. The student must recognise that he is attempting to learn something of a really testing subject. Professor A. V. Stephens, writing of training for aeronautical engineering as a career, says:

> "If I am in an expansive mood . . . . I begin by saying that aeronautical engineering is just a sophisticated form of mechanical engineering. After all, an aeroplane is a machine, but it is a particularly difficult machine to design, construct, and operate . . . . The external shape of most machines does not matter, but that of an aeroplane is vital . . . . The aeroplane designer . . . . must find a shape which gives low drag . . . . high lift . . . . adequate stability . . . . must devise a structure to fit inside it: a structure strong enough to carry the high loads that result from high speed, and sufficiently rigid to refrain from flutter. And above all it must be light."

This is the kind of challenge to keep before the student.

I should now like to offer some thoughts on training at different levels; while my own, they are not new and are indeed almost obvious common sense—or so I dare to hope.

7.1. CRAFT APPRENTICES

We must begin, I think, at the craftsman level, by making sure that the adventitious methods of the past—the handing-on of a craft from one generation to the next, with its obvious hazards—are replaced by something more formal. Much of the resistance to developments in automation could, I believe, be avoided if the new apprentice were always placed in the hands of an instructor, versed in modern methods and himself trained in instruction. Workshop methods were, until recently, largely empirical and traditional; we have now (as Goodlet says) entered on an era in which workshop methods are the result of scientific and operational research. In this new era, workpeople are no longer reliable teachers for our student mechanics and engineers. We need, therefore, trade schools attached to a works, or perhaps one school serving a group of small works; here the craftsman of the future should be carefully and formally trained in the latest developments of his art.

7.2. ENGINEERING APPRENTICES

The training of an engineering apprentice can, I think, follow existing lines in the main, but with some change of emphasis. The greatest need is for the building-on of sandwich courses to the present day-release system: initially perhaps as an addition, but later largely as an alternative. A continuous period in a technical college of, say, several weeks can clearly achieve more than an equivalent number of days at the rate of one a week. More important, the leavening of liberal studies which I have stressed already, is clearly more difficult to integrate into a day-release form of training than into a sandwich course. Ultimately, we may well find that such sandwich courses are best conducted in residential colleges, the desirability of which I need hardly stress. Provision of residential accommodation will be expensive, but it may be found that we cannot afford not to afford it.

Courses of this kind may well mean the substitution of National Diplomas for National Certificates in many cases; they may also lead to the selection of certain students for training in courses leading to the Diploma in Technology. It is apparent, I think, that such courses will need to cater not only for those who have begun a conventional training and who have achieved, say, an Ordinary National Certificate, but also for those who have remained at school to obtain advanced level passes in the General Certificate of Education. But whether the goal achieved is the Higher National Diploma or Diploma in Technology, I am certain that continuous courses of the kind suggested will produce better men.

7.3. UNDERGRADUATE APPRENTICES

University training will have to expand in volume, but I would not wish to see any appreciable change in method or approach. Nor would I wish to see the setting-up of "Technological Universities" (in passing, the word "University" implies to me a cross-section of all knowledge, which cannot therefore be associated with a single discipline*). I would, in fact, most strongly

*Chambers's English Dictionary gives "university" as deriving from the Latin "universitas—a corporation" with the root "universus" from which "universal" also derives.

oppose any suggestion that engineering as a discipline should be removed *in toto* from universities and concentrated in separate institutions. Engineers have much to learn from, as well as much to contribute to, university life. A powerful plea for the retention of engineering as a proper university discipline was made last year by a lawyer, Professor J. L. Montrose, in his Presidential Address to the Association of University Teachers. He founded his plea on the essential creativeness of application, and on the actuality of the existence of really scientific activity within departments of engineering.

> "It is not merely a pious aspiration but a practised reality that in many instances undergraduates in these departments are keenly interested in, and devote much time to, pure science; and the research work done by their staffs has been a valuable contribution to theoretical understanding of nature, and to scholarship in general."

Fortunately, it is now declared Government policy to expand engineering and science faculties within universities, and already substantial funds have been made available for capital expansion. In the University of Bristol, the Engineering Faculty has been provided with a new building which, when finished, will have cost about £1¼ million; it has enabled the Faculty to increase its undergraduate numbers from about 70 in the late 1930's to over 300 at present; and further expansion will take place in the future. Certainly we shall not lack students, it seems; over 1,200 applicants have already knocked at our doors for the 1957/58 Session, and not many more than 100 can at present be admitted.

I must say here a word about the "undergraduate apprentice" scheme being operated by the larger industrial organisations: the 1-3-1 scheme, in which the student spends a pre-university year of training in his firm, then three years following the normal university course, and finally completes his apprenticeship with a year of graduate training again at his firm. I like this system immensely. The schoolboy, whose previous training has been concerned largely with the study of natural laws, is often at a loss when he comes newly into the university discipline of engineering, and his studies of such things as heat engines, structures, and mechanics of fluids lack the stature of reality. The student who has spent a year in industry—provided the year has been properly planned, with the right balance of theory and practice—is far better equipped; he has a maturity and a sense of perspective which is astonishing in view of the short time which has elapsed since his schooldays. Perhaps—indeed probably—it is at least as much due to the acquaintance he has made with a large body of organised people as with the machines he has handled. The 1-3-1 scheme is now widely operated by aircraft and electrical firms; it is, of course, far less applicable in civil engineering, but I could wish more mechanical engineering firms employed it.

I ought here also, in honesty, to declare my view of half-year sandwich courses. While I like these for technical colleges, I do not approve of them, in general, for universities. The essential feature of a university education, without any shadow of doubt, is that while a student is training himself in one particular discipline, he is doing it in a company of people whose interests cover the whole field of human knowledge; in all the full compass of student activity and enquiry, the engineer is rubbing shoulders with the doctor, the lawyer, the priest, the biologist, the abstract scientist and the classical historian—with, in fact, the humanity he is training himself to serve. Nothing, in my view, should be allowed to mark him down as a different kind of student: one who is not there all the time, and therefore not fully a member of the body corporate. And since this must happen if he goes off to begin his six months in industry while his fellows are keeping the summer term, I do not approve of this form of the sandwich scheme. It is perhaps to be conceded that it may be operated in a very few places to meet a limited special need; but it is most interesting to notice that in the University of Glasgow, which has operated it for many years (but in which the two term system applied originally to all Faculties) there is a move to abandon it for the normal university system.

7.4. POST-GRADUATE AND ADVANCED COURSES

It is becoming clear that for students who have achieved a Higher National Certificate or Diploma, Diploma in Technology, or University degree, there is scope—in some instances at least—for formal post-graduate training. The subject of production engineering, mentioned above, provides an example. Many students at the present time do, of course, undertake such training, often in their own time, but it may well be that such courses should be formalised and condensed. Finally, we may have to have some national colleges for advanced training. The College of Aeronautics has made a beginning in the Aircraft Industry, and production is one of the courses offered. As regards engineering as a whole, I am frankly seeing through a glass, darkly; it would clearly be desirable to provide advanced and refresher courses for more senior members of the industry, although how the financial, economic, and social difficulties involved would be solved is a matter for speculation for those brave enough to do so. Some beginnings have been made in the post-war years, and developments of these must be awaited.

8. The Status of the Engineer

I have really concluded my observations on education, but cannot miss this opportunity of making some remarks on a related matter of great importance: the improvement of the status of the professional engineer. At the beginning of this lecture I remarked on the way in which the status of the engineer has varied through the years; and since if engineering falls low in the public esteem it will be difficult to recruit those we wish to train, the question of status is extremely pertinent to our general subject.

That there has been a prejudice against engineering in the past is undeniable. The engineer has been

regarded as one who got his hands dirty, and so was socially unacceptable; more insidious, perhaps, is the view—still held by some headmasters—that a boy who is not bright but is "good with his hands" is suitable for academic training in engineering. This prejudice is rapidly disappearing, and is far less noticeable now than it was even 10 years ago. No doubt the economic importance of engineering, the patent fact that a large part of scientific research relates to, or is derived from, industrial problems, even the fact that an increasing number of executives of industry hold doctorates, is responsible for the change. But we are still far from the position which obtains on the Continent and in Russia, where the professional engineer has a status as high as anyone in the land. And since the climate of opinion does vary with the years, we not only have to obtain recognition of engineering as a professional subject comparable with medicine, the Church, and the law, but to ensure that such recognition is retained.

A certain amount can be done by personal contacts and through publications. For example, to do my bit I sometimes quote my own personal history: at Cambridge I read mathematics and then studied atomic physics under Rutherford, J. J. Thomson, and others. The slump years were beginning when I graduated, and I took—as a stop-gap job only—a post in aerodynamics. Since then I have been adopted into the profession of engineering, and have always found a challenge and an intellectual satisfaction in my work which is at least equal to anything I had met in mathematics or abstract science. Again, it seems to me that not enough is made of the way in which engineering joins hands with the humanities as well as the sciences, a point I have already stressed here. Indeed, I think myself that engineering joins hands often with the pictorial and emotional arts: for example, it is certainly true that the successful aircraft designer is an artist as well as a scientist. Much of the basic work relies on scientific principles; but the integrated whole relies frequently on an emotional certainty that one design is right and the others wrong. The country as a whole needs an awareness of these things.

To my mind, however, the practical measure which we require is a legal protection of the word "engineer." To secure this, I believe we should have a Federation of Professional Engineers, to which such chartered bodies as the professional Institutions and the Royal Aeronautical Society would belong; and the corporate members of the Federation should be registered as, for example, Chartered Engineers, just as doctors and lawyers are registered. I know that there are many difficulties in this proposal, but I think also it has much to offer. Relatively minor possibilities, but quite advantageous ones, are, for example, that such a Federation could have offices in various parts of the country with individual accommodation for the autonomous constituent bodies, but with common user general facilities; the interchanges of ideas made possible by such an arrangement could clearly be enormously valuable. But the principal thing would be that such a Federation would have a common policy in relation to the status of the profession of engineering, and would give the profession the standing in the public esteem which is so vitally important.

9. Conclusion

In an earlier paragraph I criticised the tendency of some students to be prolix and circumlocutory, and I am now painfully aware that my pen has run far beyond the limits I originally set for this lecture. Perhaps, therefore, I ought to try to pick out the points I regard as important in my specification. It is not an easy specification, and he who conforms to it may be something of a paragon, but it is vital, I think, that we try to achieve it. Here, then, is a list of the matters of moment as I see them.

(*i*) We must keep the British system, expand it, and build on to it methods from abroad which can produce necessary improvements.

(*ii*) Emphasis must be laid on the fact that engineering stands between the abstract sciences and the humanities, and has important contacts with both.

(*iii*) Schools should be encouraged to train intending engineers in both the humanities and the sciences, with emphasis on the common subject of mathematics.

(*iv*) Fluency, clarity, and economy in the use of English are very important.

(*v*) On the humanist side, we require to give more attention to economics and management, history, and industrial psychology: on the scientific side, to the problems of production.

(*vi*) Educational curricula should make it clear that engineering offers a challenge, and that both work and training in the profession can give real intellectual satisfaction.

(*vii*) We must keep the flexibility of our present methods, by retaining a variety of avenues of learning and of qualifications to attempt.

(*viii*) Day-release methods must increasingly give way to "sandwich" schemes.

(*ix*) Craftsmen should be educated in trade schools by instructors versed in the latest methods.

(*x*) Engineering apprentices—those who will later become professional engineers—should be increasingly trained by "sandwich" courses in residential colleges.

(*xi*) Engineering faculties in universities must expand; the 1-3-1 undergraduate apprentice system should be more widely used; post-graduate courses in special subjects should be provided.

(*xii*) The status of the engineer must be enhanced, possibly by the formation of a Federation of Professional Engineers and by registration of Chartered Engineers.

Finally, if this summary may itself be paraphrased, we must recognise that, in engineering as in all other aspects of human knowledge, the purpose of education is to teach the student to educate himself.

The Use of Normal Modes in Problems of Forced Vibration and Impact

by

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SUMMARY:— A simple exposition, using d'Alembert's principle and methods of virtual work, is given of the properties and applications of the normal modes of vibration of a linear elastic system. The use of the normal modes in problems of free and forced vibration and dynamic loading is discussed with the aid of simple examples, and it is shown that by these methods dynamical problems for any linear system may be solved without the use of the fundamental equations of motion, provided the natural frequencies and modes of the system are known. In most problems the solutions converge rapidly, so that only the first few modes of vibration need be considered, and in these cases the solution may be modified to give further improvement in convergence. Unsatisfactory convergence may be obtained, however, in problems where there is an exciting force of very high frequency, or an impact of short duration. An approximate allowance may be made for damping, provided this is small.

1. Introduction

It is more than 80 years since Lord Rayleigh[1] published the first edition of his book "The Theory of Sound," which contains so much of the foundations of modern methods of vibration analysis. In particular Rayleigh demonstrated the properties of the normal modes of vibration, and showed how they may be used to extend the simple analysis of the single-degree-of-freedom system to those having many degrees of freedom. His methods were based on Lagrange's equations, and a similar approach is used in modern textbooks on theoretical mechanics (*e.g. see* Timoshenko and Young[2]). For this reason, a discussion of the properties and applications of the normal modes is usually regarded as being outside the scope of the less advanced books written for the vibration engineer (*e.g. see* Thomson[3]), although such books normally deal quite thoroughly with methods for determining the natural frequencies and modes.

This aspect of vibration analysis is of great practical importance, however, since it enables the behaviour of any linear elastic system under dynamic loading to be predicted *without reference to the fundamental equations of motion,* provided the natural frequencies and modes of the system are known. Of course, for simple systems, the natural frequencies and modes themselves would normally be obtained from the equations of motion, but several methods of numerical approximation are available which avoid the use of these equations, and such methods would usually be used for more complicated systems. Alternatively, the natural frequencies and modes may be determined by experimental methods.

In this paper the author presents an alternative treatment of the subject, in which the properties of the modes are derived by the use of d'Alembert's principle, and methods of virtual work. The solutions of problems of free and forced vibrations, and of dynamic loading, are discussed in conjunction with simple examples.

NOTATION

$a_n, b_n, \ldots$	deflections of N-mass system in n^{th} normal mode
E	Young's modulus
F	force
f_n	force coefficient for n^{th} mode
I	moment of inertia, 2nd moment of area of beam section
k	stiffness of spring, torsional stiffness of shaft
l	length of beam
M	mass
m	mass of beam per unit length
N	number of degrees of freedom
p	circular frequency of exciting force
t	time
t_0	duration of impact
T_n	kinetic or strain energy of n^{th} mode
$U, V.$	work done by set of forces
x	distance along beam
y	deflection
$y_n(x)$	deflection of beam for n^{th} mode
θ	angular displacement
ϕ	normal co-ordinate
ψ	phase angle
ω_n	natural circular frequency of n^{th} mode
Ω	angular velocity
ζ_n	damping factor

2. Recapitulation of Elementary Theory

The simple one-degree-of-freedom system, without damping, may be represented analogously by the mass-and-spring system shown in Fig. 1, having the equation of motion

$$M\ddot{y}+ky=F(t) \quad . \quad . \quad . \quad (1)$$

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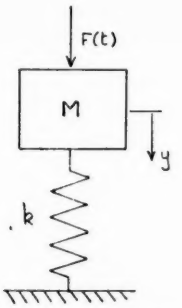

FIGURE 1. Simple system with one degree of freedom.

where y is the displacement, $F(t)$ is an external force impressed on the mass, and dots denote differentiation with respect to time. Equation (1) may be written in the form

$$\ddot{y}+\omega^2 y=\omega^2\frac{F(t)}{k} \quad . \quad . \quad (2)$$

where $\omega=\sqrt{(k/M)}$ is the natural circular frequency of the system. In the case of free vibrations, $F(t)=0$ and the solution of equation (2) is

$$y=y_0\cos\omega t+\frac{\dot{y}_0}{\omega}\sin\omega t \quad . \quad . \quad (3)$$

where y_0 and $\dot{y}_0$ are respectively the initial displacement and velocity of the mass. For forced vibrations $F(t)$ may be written $F_0 \sin pt$, where F_0 is the amplitude and p the circular frequency of the exciting force. The steady-state response of the system is now given by the Particular Integral of equation (2),

$$y=\frac{F_0}{k}\cdot\frac{\omega^2}{\omega^2-p^2}\sin pt \quad . \quad . \quad (4)$$

In equation (4) the quantity F_0/k is the static or equilibrium deflection of the mass due to a force F_0, while the quantity $\omega^2/(\omega^2-p^2)$ is frequently called the *magnification factor*.

3. Free Vibrations of Systems with Several Degrees of Freedom

A system (without damping) having a finite number (N) of degrees of freedom may again be regarded as analogous to a system of N masses, (M_a, M_b, ... and so on), restrained and interconnected by light springs. There are now N equations of motion of the form

$$\left.\begin{aligned} M_a\ddot{y}_a+k_{aa}y_a+k_{ab}y_b+\ldots. &= F_a(t)\\ M_b\ddot{y}_b+k_{ba}y_a+k_{bb}y_b+\ldots. &= F_b(t)\\ \ldots\ldots\ldots &= \ldots \end{aligned}\right\} \quad . \quad (5)$$

and so on, where y_a, y_b, ... are the displacements and $F_a(t)$, $F_b(t)$, ... the forces impressed upon the masses.

We may also envisage a system, as for example a continuous beam, which has a distributed flexibility and inertia, and therefore an infinite number of degrees of freedom. Physically, of course, all systems must be of this type, and the system with a finite number of degrees of freedom is essentially a mathematical idealisation. In a practical system of the type shown in Fig. 1 the distributed mass of the springs and the elasticity of the "lumped" mass will often be comparatively small, so that such an idealisation is permissible, while even in more continuous systems the reduction of the system to one of restricted freedom by replacing the distributed mass by a series of lumped masses will in many cases give a satisfactory approximation.

The free vibrations of the N-mass system are obtained by solving equations (5) with $F_a(t)=F_b(t)=\ldots=0$. It may be shown from the theory of ordinary differential equations, and from considerations of the conservation of energy, that there are N different types of harmonic vibration possible, each having, in general, a different natural frequency. In each of these possible forms of vibration, all parts of the system vibrate in phase, or in anti-phase, with one another, and in a fixed *natural mode* of deflection, which remains constant during the cycle of vibration. Thus all parts of the system reach their maximum deflection simultaneously. Expressed mathematically, equations (5) yield N possible solutions, each of the form

$$[y_a, y_b, \ldots]=[a_n, b_n, \ldots]\sin(\omega_n t+\psi_n) \quad (6)$$

in which the ratios of the amplitudes a_n, b_n, ... to one another (but not their absolute magnitudes) are fixed.

The most general free vibration of the system consists of a superposition of all the possible harmonic vibrations of the form (6). Since each harmonic component provides two disposable constants (the phase angle ψ_n and *one* amplitude) there is a total of $2N$ disposable constants to satisfy the $2N$ initial conditions, *i.e.* the initial displacement and velocity of each mass.

In the case of the transverse vibrations of a beam, (Fig. 2) representing a continuous system, there is an infinite number of possible harmonic vibrations, each of the form

$$y(x)=y_n(x)\sin(\omega_n t+\psi_n) \quad . \quad (7)$$

where $y(x)$ is the transverse displacement, and $y_n(x)$ is the natural mode of deflection associated with the n^{th} natural frequency ω_n. Again, all parts of the beam vibrate in phase or in anti-phase with one another.

A *normal mode* of vibration is defined by attaching definite numerical values to the deflections at various points, these values being chosen to give the correct natural mode shape. Henceforth, the symbols a_n, b_n, ... will be assumed to have given numerical values which define the n^{th} normal mode of the N-mass system. The normal modes of vibration of the beam will be similarly specified by definite functions $y_n(x)$.

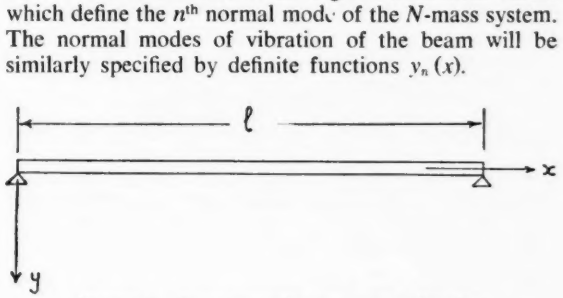

FIGURE 2. Beam executing transverse vibration.

4. Properties of the Normal Modes

By introducing suitable inertia forces (d'Alembert's principle) the dynamical problem of the vibration of an elastic system may be reduced to a statical one. When such a system is executing free vibrations in a normal mode, the maximum inertia forces occurring during a cycle of vibration define a set of forces which may conveniently be called a "*natural force set*,"* and there will be one such natural force set associated with each normal mode. Thus, for the N-mass system the maximum accelerations for the n^{th} mode are, from equation (6), $-\omega_n^2 a_n$, $-\omega_n^2 b_n$, ... and the natural force set consists of forces $M_a\omega_n^2 a_n$, $M_b\omega_n^2 b_n$, ... acting on the masses M_a, M_b, ... respectively. In the case of the beam, the natural force set consists of a distributed lateral force of magnitude $m\omega_n^2 y_n(x)$ per unit length, where m is the mass of the beam per unit length (not necessarily uniform).

In the position of maximum deflection during a free vibration in a normal mode, the system is in equilibrium under the action of the elastic forces and the inertia forces, the latter constituting a natural force set. In other words, the equilibrium deflections produced by a natural force set are those of the corresponding normal mode. This important result states the *force-deflection property* of a normal mode.

A theorem in statics (Betti's theorem[1]) states that if two sets of forces, P_1 and P_2 say, are applied to a linear elastic system, then the work done by P_1 over the displacements produced by P_2 is equal to that done by P_2 over the displacements due to P_1. Considering the N-mass system, suppose that P_1 and P_2 are taken equal to the natural force sets for the first and second modes respectively. Then the deflections produced by P_1 and P_2 are a_1, b_1, ... and a_2, b_2, ... respectively. The work done by P_1 over the displacements due to P_2 is

$$\omega_1^2\{M_a a_1 a_2 + M_b b_1 b_2 + \ldots\} \quad . \quad . \quad (8)$$

while that done by P_2 over the displacements due to P_1 is

$$\omega_2^2\{M_a a_1 a_2 + M_b b_1 b_2 + \ldots\} \quad . \quad . \quad (9)$$

According to Betti's theorem, expressions (8) and (9) are equal. The two natural frequencies ω_1 and ω_2 will, in general be different, and it follows that

$$M_a a_1 a_2 + M_b b_1 b_2 + \ldots = 0 \quad . \quad . \quad (10)$$

Equation (10) expresses the *orthogonal property*† of the two modes, and a similar relation holds for any pair of modes.

In general the orthogonal property may be expressed in words as follows:—

"The work done by a natural force set over the displacements of any *other* normal mode is zero."

Thus, in the case of the beam, a similar proof leads to an orthogonal property in the form

$$\int_0^l m\, y_n(x)\, y_r(x)\, dx = 0 \quad . \quad . \quad (11)$$

where $y_n(x)$, $y_r(x)$ are any two normal modes, and the integration extends over the length of the beam.

The work done by a natural force set in the displacements of its *own* mode is

$$\omega_n^2\{M_a a_n^2 + M_b b_n^2 + \ldots\} \quad . \quad . \quad (12)$$

which is twice the maximum kinetic energy of the system when vibrating in the particular mode considered. From the force-deflection property it is obvious that the work done is also equal to twice the maximum strain energy of the mode. The maximum kinetic and strain energies are in fact equal since the total energy remains constant during a free vibration.

5. Normal Co-ordinates

Any deflection of an elastic system may be resolved into a series of components similar to the normal modes, *i.e.* by superimposing the different modes multiplied respectively by suitable factors ϕ_1, ϕ_2, and so on. In the case of the N-mass system, if y_a, y_b, ... are the given deflections, then the N quantities ϕ_1, ϕ_2, ... and so on may be determined from the N equations

$$\left.\begin{aligned} y_a &= \phi_1 a_1 + \phi_2 a_2 + \ldots\ldots + \phi_N a_N \\ y_b &= \phi_1 b_1 + \phi_2 b_2 + \ldots\ldots + \phi_N b_N \\ \ldots &= \ldots\ldots\ldots\ldots \end{aligned}\right\} \quad . \quad (13)$$

It is clear that the quantities ϕ_1, ϕ_2, ... *the normal co-ordinates*—could be used to specify the deflection of the system in the place of the original co-ordinates y_a, y_b, ... and it will be shown later that the use of the normal co-ordinates leads to simple solutions for problems of systems with many degrees of freedom.

The values of the ϕ's may be determined very simply from equations (13) by use of the orthogonal property and the principle of virtual work. The equations state the equality of two sets of deflections, represented by the aggregates of their right and left hand sides. Accordingly, the work done by any given set of forces will be the same for both sets of deflections. Consider the work done by a natural force set for the first mode. The work done over the deflections y_a, y_b, ... is

$$U_1 = \omega_1^2\{M_a a_1 y_a + M_b b_1 y_b + \ldots\} \quad . \quad (14)$$

On the right hand side of the equations only the first mode produces any work, by virtue of the orthogonal property, and this work is equal to $2\phi_1 T_1$, where T_1 is the kinetic or strain energy of the first mode. Equating the work done, we obtain

$$\phi_1 = \frac{U_1}{2T_1} = \frac{M_a a_1 y_a + M_b b_1 y_b + \ldots}{M_a a_1^2 + M_b b_1^2 + \ldots} \quad . \quad (15)$$

In a similar way ϕ_2, ϕ_3, and so on, are easily determined.

By a similar procedure any deflection of the beam

*These natural force sets are related to the "generalised forces" in the Lagrangian method. If Q_n is the generalised force corresponding to the co-ordinate ϕ_n, then $Q_n = 2 f_n T_n$.

†This derivation has been given previously by the author in Ref. (5).

which is compatible with the boundary conditions may be resolved into normal components, thus

$$y(x)=\phi_1 y_1(x)+\phi_2 y_2(x)+\ldots \quad . \quad (16)$$

in which the normal co-ordinates are given by

$$\phi_n=\frac{\int_0^l m y_n(x)\, y(x)\, dx}{\int_0^l m\,[y_n(x)]^2\, dx} \quad . \quad . \quad (17)$$

It is also possible to resolve any set of external forces on a system into components corresponding to natural force sets, so that, for the N-mass system

$$\left.\begin{aligned} F_a&=f_1 M_a\omega_1^2 a_1+f_2 M_a\omega_2^2 a_2+\ldots \\ F_b&=f_1 M_b\omega_1^2 b_1+f_2 M_b\omega_2^2 b_2+\ldots \\ \ldots&= \quad . \quad . \quad . \quad . \quad . \end{aligned}\right\} \quad . \quad (18)$$

where F_a, F_b, ... are the given external forces, and the quantities f_1, f_2, ... are suitable factors, which, again, may be determined by the principle of virtual work. Since the sets of forces represented by the right and left hand sides of equations (18) are equivalent, the work done in any given deflection will be the same for both. By considering the work done when the system is displaced in the first mode, and by using the orthogonal property, it is found that

$$f_1=\frac{F_a a_1+F_b b_1+\ldots}{2T_1} \quad . \quad . \quad (19)$$

with similar expressions for f_2, f_3, and so on.

6. Equations of Motion in Terms of the Normal Co-ordinates

The force-deflection property for each normal mode shows that any static deflection in a particular mode necessitates the application of external forces distributed according to the corresponding natural force set, and, (by application of d'Alembert's principle), the same is true of any dynamic deflection. Conversely, it may be shown that if the external forces, whether static or dynamic, are distributed according to a particular natural force set, they will result in a deflection of the system in the corresponding mode only. (It is possible for deflections to exist in other modes simultaneously, but such deflections constitute free vibrations, and cannot be influenced by the external forces).

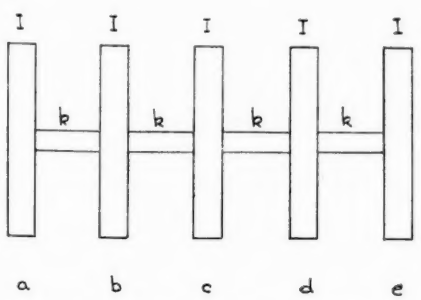

FIGURE 3. 5-mass torsional system.

In the general case, where the external forces contain components corresponding to all the natural force sets, all the modes of vibration will be excited, but in determining the response in each mode it is necessary to consider only the corresponding component of the external forces.

The derivation of the equations of motion is most concisely given in the case of the beam. The deflection in the n^{th} mode $y_n(x)$ is specified by the normal co-ordinate ϕ_n and the corresponding external force component by the coefficient f_n. In general, ϕ_n and f_n will be functions of t. The sum of the external and inertia forces gives a force per unit length equal to

$$f_n m\omega_n^2 y_n(x)-\ddot{\phi}_n m y_n(x) \quad . \quad . \quad (20)$$

But (from the force-deflection property) the force required to produce a deflection $\phi_n y_n(x)$ is

$$\phi_n m\omega_n^2 y_n(x) \quad . \quad . \quad . \quad (21)$$

Equating the quantities (20) and (21) we obtain

$$\ddot{\phi}_n+\omega_n^2\phi_n=\omega_n^2 f_n \quad . \quad . \quad . \quad (22)$$

which is the required equation for ϕ_n. An identical equation may be obtained for any system when vibrating in a normal mode.

This equation has the same form as equation (2) for the single-degree-of-freedom system, and its solution for any problem may be obtained immediately if the corresponding solution of equation (2) is available.

7. Impact Stresses in a Torsional System

As a first example in the application of the above theory, consider the torsional system shown in Fig. 3, in which, at time $t=0$, the disc (e), rotating with angular velocity Ω, is clutched on to the remainder of the system, which is at rest. Since there are no external forces acting during the subsequent motion, the problem consists of determining the free vibrations of the complete system from given initial velocities.

The first step is to determine the natural frequencies and modes of the system. This may be done by any of the standard methods, and the results are given in Table I. In the table the quantities a, b, ... are the angular displacements of the discs (a), (b), and so on, which have been chosen to define the modes of vibration. The first natural frequency is zero, and the corresponding mode is a rigid body rotation of the system. The equations for the normal co-ordinates will be of the form (22) with $f_n=0$ since there are no external

TABLE I

Mode number (n)	1	2	3	4	5
$\omega\sqrt{(I/k)}$	0	0·6180	1·176	1·618	1·902
a	1	1	1	1	1
b	1	0·6180	−0·3820	−1·618	−2·618
c	1	0	−1·236	0	3·236
d	1	−0·6180	−0·3820	1·618	−2·618
e	1	−1	1	−1	1

forces. For the first mode $\omega=0$ and the equation reduces to

$$\ddot{\phi}_1=0 \quad . \quad . \quad . \quad . \quad (23)$$

giving

$$\phi_1=\phi_{10}+\dot{\phi}_{10}t \quad . \quad . \quad . \quad (24)$$

where ϕ_{10} and $\dot{\phi}_{10}$ are the initial values of ϕ_1 and $\dot{\phi}_1$. The equation for ϕ_2 is

$$\ddot{\phi}_2+\omega_2{}^2\phi_2=0 \quad . \quad . \quad . \quad (25)$$

giving

$$\phi_2=\phi_{20}\cos\omega_2 t+\frac{\dot{\phi}_{20}}{\omega_2}\sin\omega_2 t \quad . \quad . \quad (26)$$

and similar solutions are obtained for ϕ_3, ϕ_4, ϕ_5.

The normal co-ordinates are related to the angular displacements θ_a, θ_b, ... of the discs by five equations (corresponding to equation (15)) each of the form

$$\phi=\frac{I_a a\theta_a+I_b b\theta_b+\ldots.+I_e e\theta_e}{I_a a^2+I_b b^2+\ldots.+I_e e^2}. \quad . \quad (27)$$

At time $t=0$ the shafts of the system are unstrained and the system is instantaneously in its equilibrium position. We may therefore take $\theta_a=\theta_b=\ldots=0$ initially, from which it follows that the initial values ϕ_{10}, ϕ_{20}, ... are also zero. By differentiating equation (27) with respect to t, we obtain

$$\dot{\phi}=\frac{I_a a\dot{\theta}_a+I_b b\dot{\theta}_b+\ldots.+I_e e\dot{\theta}_e}{I_a a^2+I_b b^2+\ldots.+I_e e^2} \quad . \quad (28)$$

By means of these equations the initial values $\dot{\phi}_{10}$ and so on may be obtained as follows:

$$\left.\begin{aligned}\dot{\phi}_{10}&=\ 0{\cdot}2\,\Omega\\ \dot{\phi}_{20}&=-0{\cdot}3618\,\Omega\\ \dot{\phi}_{30}&=\ 0{\cdot}2618\,\Omega\\ \dot{\phi}_{40}&=-0{\cdot}1382\,\Omega\\ \dot{\phi}_{50}&=\ 0{\cdot}0382\,\Omega\end{aligned}\right\} \quad . \quad . \quad (29)$$

The values of the normal co-ordinates at any time t are now given by equations (24), (26), and so on. The value of θ_a is then given by

$$\theta_a=\phi_1 a_1+\phi_2 a_2+\ldots.+\phi_5 a_5$$

$$=0{\cdot}2\,\Omega t+\Omega\sqrt{\frac{I}{k}}\{-0{\cdot}5854\sin\omega_2 t+0{\cdot}2227\sin\omega_3 t-$$
$$-0{\cdot}0854\sin\omega_4 t+0{\cdot}0201\sin\omega_5 t\} \quad . \quad (30)$$

Similarly

$$\theta_b=0{\cdot}2\,\Omega t+\Omega\sqrt{\frac{I}{k}}\{-0{\cdot}3618\sin\omega_2 t-0{\cdot}0851\sin\omega_3 t+$$
$$+0{\cdot}1382\sin\omega_4 t-0{\cdot}0526\sin\omega_5 t\} \quad . \quad (31)$$

with similar equations for θ_c, θ_d, and θ_e.

Multiplying the angle of twist by the torsional stiffness, the torque in the shaft ab is obtained as follows

$$\Omega\sqrt{(kI)}\{-0{\cdot}2236\sin\omega_2 t+0{\cdot}3078\sin\omega_3 t-$$
$$-0{\cdot}2236\sin\omega_4 t+0{\cdot}0727\sin\omega_5 t\} \quad . \quad (32)$$

with similar expressions for the torques in the other shafts.

The resultant torque in each shaft consists of a number of harmonic components having the natural frequencies of the system. Since the frequencies are not simply related to one another, the resultant torque variation is non-periodic, and the determination of the absolute maximum is not easy. One assumption which may be made is that at some instant approximate coincidence of the individual component maxima will be obtained, giving a resultant equal to the sum of the component maxima. In practice such a procedure may considerably over-estimate the maximum torque, owing to the die-away of the vibrations due to damping. A better approximation may be obtained by plotting the total torque variation during the first few cycles of the fundamental frequency.

8. Forced Vibrations

When the N-mass system is excited by harmonic external forces, $F_a\sin pt$, $F_b\sin pt$, ... the normal co-ordinate equations have the form

$$\ddot{\phi}_n+\omega_n{}^2\phi_n=\omega_n{}^2 f_n'\sin pt \quad . \quad . \quad (33)$$

where f_n' is the force coefficient corresponding to the external forces F_a, F_b, and so on. As in the case of the single-degree-of-freedom system, the steady-state forced vibrations are given by the Particular Integral of equation (33), namely

$$\phi_n=f_n'\frac{\omega_n{}^2}{\omega_n{}^2-p^2}\sin pt \quad . \quad . \quad (34)$$

We note that, as in equation (4), $\phi_n=f_n'$ gives the equilibrium deflection in the mode due to the external forces, while the factor $\omega_n{}^2/(\omega_n{}^2-p^2)$ is the familiar expression for the magnification factor.

As an example consider a problem in which a uniform beam, simply-supported at each end, is excited by a concentrated force $F_0\sin pt$ applied at its mid-point. Choosing x- and y- co-ordinates as in Fig. 2, the natural frequencies and modes are given by

$$\omega_n=\frac{n^2\pi^2}{l^2}\sqrt{\left(\frac{EI}{m}\right)} \quad . \quad . \quad (35)$$

$$y_n(x)=\sin\frac{n\pi x}{l} \quad . \quad . \quad . \quad . \quad (36)$$

where EI is the flexural rigidity of the beam, and $n=1$, 2, 3, for the 1st, 2nd, 3rd modes, and so on. The natural force set for each mode consists of a distributed force of magnitude $m\omega_n{}^2\sin(n\pi x/l)$ per unit length.

Omitting for the moment the factor $\sin pt$, a force F_0 at the mid-point of the beam may be resolved into a series of natural force sets, thus

$$f_1'm\omega_1{}^2\sin\frac{\pi x}{l}+f_2'm\omega_2{}^2\sin\frac{2\pi x}{l}+\ldots \quad (37)$$

where the force coefficients may be determined as before by imagining that the beam is given virtual displacements in each mode in turn, and by using the principle of virtual work. Remembering that each natural force

set does no work except in the displacements of its own mode, the force coefficients are evaluated as

$$f_n' = \frac{V_n}{2T_n} \quad . \quad . \quad . \quad (38)$$

where V_n is the work done by the force F_0 in the displacements of the n^{th} mode, and T_n is the maximum kinetic or strain energy of the mode. Proceeding in this way the values obtained are

$$f_n' = \frac{2F_0 l^3}{n^4\pi^4 EI} \sin(\tfrac{1}{2}n\pi) \quad . \quad . \quad (39)$$

In determining the force coefficients by this method, *it is not necessary to evaluate the natural force sets* in equation (37) since it is known that the work done by a natural force set in the displacements of its own mode is $2T_n$. For the even-numbered modes there is a mode at the centre of the beam and f_n' is zero. These modes, being skew-symmetrical, are not excited by a centrally applied force.

The value of ϕ for each mode is now obtained from equation (34), and from equation (16) the resultant deflection of the beam is given by

$$y(x) = \frac{2F_0 l^3}{\pi^4 EI} \sin pt \sum_{n=1}^{\infty} \frac{1}{n^4} \frac{\omega_n^2}{\omega_n^2 - p^2} \sin(\tfrac{1}{2}n\pi) \sin\left(\frac{n\pi x}{l}\right) \quad . \quad . \quad . \quad (40)$$

If the exciting frequency coincides with any of the natural frequencies, the magnification factor for that particular mode becomes infinite, giving the case of resonance. In practice the resonant amplitude is limited by the damping in the system, which has so far been neglected. This will be considered later.

In a problem dealing with a system having an infinite number of degrees of freedom, it is important that the solution should converge rapidly, so that an accurate result may be obtained by using only the first few modes of vibration. This is especially important where the modes are determined by numerical approximation, since considerable labour is involved in determining the higher modes. In this particular problem a satisfactory convergence is in fact obtained. However, Rayleigh[1] has indicated a method by which the convergence may be further improved. It is seen that the magnification factor is approximately unity if $\omega_n \geqslant p$, so that for the higher frequency modes the response differs little from the equilibrium deflection. By separating the response in each mode into two components, consisting of the equilibrium deflection and an "incremental dynamic component," the series (40) may be written in the alternative form

$$y = \frac{2F_0 l^3}{\pi^4 EI} \sin pt \sum_{n=1}^{\infty} \frac{1}{n^4} \sin(\tfrac{1}{2}n\pi) \sin\left(\frac{n\pi x}{l}\right) + \\ + \frac{2F_0 l^3}{\pi^4 EI} \sin pt \sum_{n=1}^{\infty} \frac{1}{n^4} \frac{p^2}{\omega_n^2 - p^2} \sin(\tfrac{1}{2}n\pi) \sin\left(\frac{n\pi x}{l}\right) \quad (41)$$

Now, omitting the factor $\sin pt$, the first series in equation (41) represents the sum of the equilibrium deflections in all the modes due to a centrally applied force F_0, and this is equal to the resultant equilibrium deflection of the beam, which is

$$\frac{F_0}{48EI}\{3l^2x - 4x^3\} \ , \left(0 \leqslant x \leqslant \frac{l}{2}\right) \quad . \quad (42)$$

In the remaining series the values of the factors $p^2/(\omega_n^2 - p^2)$ approach zero when $\omega_n \geqslant p$. Consequently, all modes may be neglected whose natural frequency is large compared with the exciting frequency.

9. Dynamic Loading Problems

In the general case of dynamic loading, the external forces vary with time in some given manner over an interval, usually chosen as starting at $t=0$. In addition initial values of the displacement and velocity are specified. In the single-degree-of-freedom system it is necessary to determine the complete solution of equation (2) for the given force $F(t)$. When $F(t)$ is a simple function, an analytical solution may sometimes be found. In other cases (for example when $F(t)$ is given in numerical form) graphical and numerical methods of solution are available, (*e.g. see* Timoshenko and Young[2], Bishop[6]). The same procedures may be used for systems having many degrees of freedom, by virtue of the similarity of equations (2) and (22).

As an example, consider the deflection produced in a simply-supported beam by a centrally applied force having the time variation shown in Fig. 4, *i.e.*

$$F = F_0 \sin\frac{\pi t}{t_0} \ , \quad (0 \leqslant t \leqslant t_0) \quad . \quad (43)$$

During the impact each normal co-ordinate equation has the form

$$\ddot{\phi}_n + \omega_n^2 \phi_n = \omega_n^2 f_n' \sin\frac{\pi t}{t_0} \quad . \quad . \quad (44)$$

where f_n', the force coefficient corresponding to a central force F_0, is given by equation (39). The solution of equation (44), assuming ϕ_n and $\dot{\phi}_n$ are initially zero, is

$$\phi_n = \frac{\pi f_n' \omega_n t_0}{\pi^2 - \omega_n^2 t_0^2}\left\{\sin\omega_n t - \frac{\omega_n t_0}{\pi}\sin\frac{\pi t}{t_0}\right\} . \quad (45)$$

After the impact, ϕ_n is given by

$$\ddot{\phi}_n + \omega_n^2 \phi_n = 0 \quad . \quad . \quad . \quad (46)$$

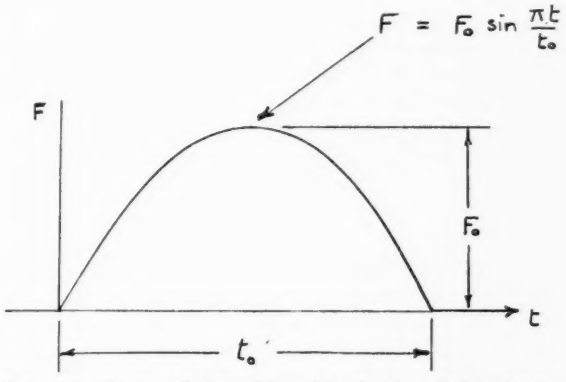

FIGURE 4. Time variation of impulsive load applied to beam.

with the condition that, at $t=t_0$, the values of ϕ_n and $\dot{\phi}_n$ are equal to those given by equation (45). The appropriate solution is

$$\phi_n = \frac{2\pi f_n' \omega_n t_0}{\pi^2 - \omega_n^2 t_0^2} \cos \frac{\omega_n t_0}{2} \sin \omega_n \left(t - \frac{t_0}{2} \right) \qquad (47)$$

(In the special case when $\omega_n = \pi/t_0$, the solutions (45) and (47) have a modified form).

The deflection at any point of the beam is now obtained by substitution in equation (16), giving

$$y = \frac{2F_0 l^3}{\pi^3 EI} \sum_{n=1}^{\infty} \frac{1}{n^4} \sin (\tfrac{1}{2}n\pi) \frac{\omega_n t_0}{\pi^2 - \omega_n^2 t_0^2} \left\{ \sin \omega_n t - \right.$$
$$\left. - \frac{\omega_n t_0}{\pi} \sin \frac{\pi t}{t_0} \right\} \sin \left(\frac{n\pi x}{l} \right) \qquad (48)$$

during the impact, and

$$y = \frac{4F_0 l^3}{\pi^3 EI} \sum_{n=1}^{\infty} \frac{1}{n^4} \sin (\tfrac{1}{2}n\pi) \frac{\omega_n t_0}{\pi^2 - \omega_n^2 t_0^2} \cos \frac{\omega_n t_0}{2} \times$$
$$\times \sin \omega_n (t - \tfrac{1}{2}t_0) \sin \left(\frac{n\pi x}{l} \right). \qquad (49)$$

after impact.

Equations (48) and (49) each contain a series of harmonic oscillations of different frequencies, and to be of practical value it is again essential that rapid convergence is obtained. To examine this problem further, consider the case in which the impact duration is long compared with natural period of the mode, so that $\omega_n t_0 \geqslant 2\pi$. We may neglect π^2 in the denominator in equation (45) and obtain the approximation

$$\phi_n \simeq f_n' \sin \frac{\pi t}{t_0} - \frac{\pi}{\omega_n t_0} f_n' \sin \omega_n t \qquad . \qquad (50)$$

The first term in this approximation is simply the equilibrium value of ϕ_n corresponding to the external force $F_0 \sin (\pi t/t_0)$, while the second term represents a negligibly small free vibration. It is thus sufficiently accurate to treat the applied force as a static one for such a mode. Following a method used by Williams[7, 8], a more convergent solution may therefore be obtained by separating the response in each mode into the equilibrium response, together with an incremental dynamic component, by writing equation (45) in the form

$$\phi_n = f_n' \sin \frac{\pi t}{t_0} + \frac{f_n' \pi \omega_n t_0}{\pi^2 - \omega_n^2 t_0^2} \left\{ \sin \omega_n t - \frac{\pi}{\omega_n t_0} \sin \frac{\pi t}{t_0} \right\} \qquad (51)$$

By summing separately the equilibrium and incremental deflections in all the modes, the total deflection of the beam during impact may be written

$$y = y_0 \sin \frac{\pi t}{t_0} + \frac{2F_0 l^3}{\pi^3 EI} \sum_{n=1}^{\infty} \frac{1}{n^4} \sin (\tfrac{1}{2}n\pi) \frac{\omega_n t_0}{\pi^2 - \omega_n^2 t_0^2} \left\{ \sin \omega_n t - \right.$$
$$\left. - \frac{\pi}{\omega_n t_0} \sin \frac{\pi t}{t_0} \right\} \sin \left(\frac{n\pi x}{l} \right). \qquad (52)$$

where y_0 is the equilibrium deflection due to a central force F_0, given by equation (42). In the series in equation (52) all the higher modes, whose natural period is short compared with t_0, may be neglected.

Provided that the impact duration is not very short compared with the fundamental natural period of the beam, it is found that the solutions given by equations (49) and (52) converge sufficiently rapidly for numerical computation. Thus, if t_0 is equal to 1/10 of the fundamental period, the maximum bending moment in the beam may be determined within about 4 per cent by considering the first and third modes only. On the other hand, if the impact duration is very short, the convergence is less satisfactory. In determining the bending moment at the centre, for example, it is found that the contributions are approximately equal for all modes whose period is long compared with the impact, and consequently a large number of modes may have to be taken into account. Where this difficulty arises an alternative solution in terms of stress-wave propagation may give a more accurate result (*e.g. see* Bishop[9], Jones[10]). However, such solutions are difficult to obtain except in simple cases, and further discussion lies outside the scope of this paper.

10. Effect of Damping

It is not possible to extend the normal-mode method of analysis to the general case of damped systems without considerable complication, since the damping forces (in general) introduce a coupling effect between the normal modes, and it is not permissible to consider each mode separately. However, if the damping forces are distributed in a manner similar to either the inertia or elastic forces, or consist of a combination of such distributions, then no coupling effect arises. In these cases the analysis may be extended fairly easily to include the effect of damping.

In most practical problems the nature and distribution of the damping forces are not known precisely. If, as is usual, the damping forces are small and well distributed, it is reasonable to neglect coupling and treat each mode independently. On the other hand, where considerable damping is introduced, for example, by means of an isolated damper, the coupling effects may be important.

If coupling due to damping is absent, the equations for the normal co-ordinates of a damped system have the form

$$\ddot{\phi}_n + \beta_n \dot{\phi}_n + \omega_n^2 \phi_n = \omega_n^2 f_n \qquad . \qquad . \qquad (53)$$

where the additional term $\beta_n \dot{\phi}_n$ is due to the damping forces, assumed proportional to the velocity. This equation is again similar to that of a single-degree-of-freedom system, and the usual methods of solution may be applied. Using the notation

$$\zeta_n = \frac{\beta_n}{2\omega_n} \qquad . \qquad . \qquad . \qquad . \qquad (54)$$

equation (53) may be written

$$\ddot{\phi}_n + 2\zeta_n \omega_n \dot{\phi}_n + \omega_n^2 \phi_n = \omega_n^2 f_n \qquad . \qquad . \qquad (55)$$

The case $\zeta_n = 1$ gives critical damping, so that the factor ζ_n represents the *damping factor*[3] of the mode considered. A value of ζ_n for each mode may be estimated by means of a resonance test on the system.

In the case of forced vibrations, where $f_n = f_n' \sin pt$, it is readily shown that if the damping is small, it may

be neglected except in the region of resonance. In the case of resonance in a lightly damped system with several degrees of freedom, therefore, the response in the non-resonant modes will be given approximately by equation (34). For the resonant mode, in which $p=\omega_n$, the solution of equation (55) is

$$\phi_n = -\frac{1}{2\zeta_n} f_n' \cos pt \quad . \quad . \quad (56)$$

in which the phase lag of 90° should be noted. The amplitude of vibration in the resonant mode will be large compared with that in other modes, so that it is usually sufficiently accurate to consider only the response in the resonant mode.

Damping may also be taken into account in dynamic loading problems by use of equation (55). In practical systems, however, the damping is usually small and its effect insignificant.

11. Conclusions

By expressing the deflection of an elastic system in terms of the normal co-ordinates, simple solutions may be obtained for problems of forced vibration or impact. To use the method it is necessary to know the natural frequencies of the system, the shapes of the normal modes, and the kinetic or strain energy associated with each mode. (In practice it is usually easier to calculate the kinetic energy). If dynamic stresses are to be determined, the stress distribution for each normal mode must also be known.

The method enables solutions to be obtained for elaborate systems without setting up and solving the fundamental equations of motion, since the natural frequencies and modes may be determined by numerical methods of approximation, by the use of analogues, or by direct experiment.

To reduce the labour of computation, it is important that rapid convergence is obtained, so that only the first few modes need be considered. In most problems there is good convergence, provided that, in the case of forced vibrations, not many natural frequencies lie below the exciting frequency, or, in the case of impact, that the impact duration is not very short compared with many of the natural periods of the system.

The method of analysis may be extended to take approximate account of damping, when this is small.

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TECHNICAL NOTES

The Relative Commercial and Operational Properties of Short-Range Transport Aeroplanes Powered by Turbine and Reciprocating Engines

by

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THERE HAVE recently appeared a number of papers and notes bearing on the merits of turbo-prop vis-a-vis turbo-jet transport aeroplanes, mostly exhibiting specific favour towards one type or the other, but disagreeing among themselves and all based upon investigations which, it is contended here, are incomplete.

The basis used has invariably been a comparison of the relative direct operating costs per unit of weight (*i.e.* per passenger or per ton) per mile, and the relative earning capacities have not been considered. This, it is believed, is a serious omission which can only lead to a distorted assessment and erroneous conclusions.

The author has been associated with a thorough-going investigation into the relative merits of twin-engined turbo-prop, turbo-jet, and reciprocating-engined aeroplanes, all designed on a strictly comparable basis to do, as far as the performance of suitable available engines would allow, the same job in terms of capacity payload and associated operational stage length, take-off and landing performance and one-engine-inoperative climb performance in given atmospheric and altitude conditions.

A précis of this investigation is presented here, in broad terms, to show the variations in, and inter-play of, the various quantities affecting the economy and other aspects of operations.

The object is to show that there is far less to choose between truly comparable aircraft with the three types of engine than is generally represented, having regard to their commercial value.

It is quite unavoidable that, during the development of the argument, appeal has to be made to figures resulting from detailed calculations for aeroplanes of the several types compared. Also, it is inevitable that there is some loss of accuracy due to the generalisations made herein in the interests of simplicity, and since profit is a small quantity in relation to both cost and revenue, $\pm$£5,000 or so, in the comparison of profits per annum per 10,000 lb. of all-up weight, should be regarded as the order of accuracy in the relevant Table.

GENERAL

While there are circumstances in which the most suitable transport aeroplane for a purpose is not the most economic one (in the sense of ability to earn a maximum profit in relation to capital investment or turnover, when the several alternatives are each used in the best manner), such is not the case for aeroplanes intended primarily for airline use.

For this sphere of commercial activity, where profit margins are usually relatively small (or negative), it seems proper to project and proceed with the manufacture of new designs of aeroplanes on a basis of their ability to provide the operator with either:—

(*i*) features to attract additional business while operating at an ordinary specific profit-earning ability —thereby improving the annual profit, or

(*ii*) an improved profit-earning ability with a given level of business, again improving the annual profit, or

(*iii*) features to attract additional business, together with an improved specific profit-earning ability, giving the greatest financial advantage.

(An increased profit-earning ability connotes also the ability, when circumstances permit, to reduce fares.)

The argument is developed below, in simple terms, with particular reference to short-range operations.

THE ARGUMENT

Clearly: PROFIT = REVENUE − TOTAL OPERATING COST.

REVENUE

If the revenue rate per passenger nautical mile (pence) is denoted by F, the block speed (knots) by V_b and the annual utilisation of the aeroplane (hours) by U, then it is easily and incontrovertibly shown that, to a very close approximation:—

$$\text{Revenue [£ (sterling)/annum/lb. of payload]} = 2\left(\frac{U}{1000}\right)\left(\frac{V_b}{100}\right)F$$

(the passenger unit weight is taken as 213 lb.)

Now if, for a given representative stage length, a given value of F is taken, regardless of the characteristics of the aeroplane operating the service, it is seen that the Revenue is proportional to UV_b—the miles per year. A number of different designs of short-range aeroplane (piston-engined, turbo-propeller-engined and turbo-jet-engined) all in the same general size class, have been examined on a strictly comparative basis, with the results given in Table I. It is assumed that the working day consists of 14 hours, the working year of 286 days; the product of these two numbers—4,000 hours—may be described as a common "gross" utilisation, which exceeds the actual utilisation (U) by amounts depending on the block speed and the turn-round time of the aeroplane in question. Still air conditions are also assumed and turn-round times (T_T) have been arbitrarily increased as the stage distance increases, but as these times exceed the re-fuelling times for turbo-jet aeroplanes of the size and range considered, the turn-round time used for each type is the same.

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TABLE I

Stage distance S. (n. m.)			200	300	500	700	900
Piston-engined	T_T (hrs.)		0·5	0·7	0·9	1·1	1·3
	U (hrs.)	(*a*)	3090	3080	3220	3270	3320
	V_b (kts.)		117	127	136	141	143
	UV_b (n. m./annum)		362,000	392,000	438,000	461,000	475,000
	UV_b/S (landings/annum)	(*b*)	1810	1307	876	659	526
Turbo-prop engined	T (hrs.)		0·5	0·7	0·9	1·1	1·3
	U (hrs.)	(*a*)	2880	2860	2980	3060	3090
	V_b (kts.)		155	171	190	198	204
	UV_b (n. m./annum)		446,000	489·000	566,000	606,000	630,000
	UV_b/S (landings/annum)	(*b*)	2230	1630	1132	866	700
Turbo-jet engined	T (hrs.)		0·5	0·7	0·9	1·1	1·3
	U (hrs.)	(*a*)	2560	2485	2590	2650	2680
	V_b (kts.)		226	261	303	324	338
	UV_b (n. m./annum)		579,000	650,000	785,000	860,000	906,000
	UV_b/S (landings/annum)	(*b*)	2895	2167	1570	1229	1007

(The aeroplanes considered in Table I were all designed to carry capacity payload of about 30 passengers over a stage length of about 300 n.m. with wing and power loadings to give a take-off performance appropriate to airfields of the feeder and trunk-line class (*i.e.* I.C.A.O. classes G. and F.) at altitude and temperature above S.L. and above the corresponding I.S.A. value respectively).

It will be observed that, for all stage distances, the Revenue for the turbo-jet aeroplane, despite a reduced utilisation (U) due to the lower block time (more frequent landing), is superior to that of the other types. The annual Revenues per lb. of Payload corresponding to the above values of UV_b, assuming the following (average) revenue rates (F): —

TABLE II

Stage distance (n.m.)	200	300	500	700	900
Pence per pass. n.m.	9·1d.	8·1d.	7·5d.	6·9d.	6·6d.

are: —

TABLE III

Piston-engined	£66	£63·5	£66	£64	£63
Turbo-prop engined	£81	£79	£85	£84	£83
Turbo-jet engined	£105	£105	£118	£119	£120

The superiority of the turbo-jet aeroplane in regard to REVENUE per lb. of Payload can hardly be doubted in the face of these figures.

TOTAL OPERATING COST

As is usual, this is divided into DIRECT and INDIRECT costs.

Direct costs

These include Amortisation of the equipped airframe, power plants and spares; Insurance (aircraft, passenger and third party liability); Maintenance and Overhaul Costs; Crew Costs; Landing Costs; Fuel and Oil Costs.

Assume that the first cost of an aeroplane to carry a given payload for a given distance is of the order of £200,000. Now a variation of ± 10 per cent of this, in association with a 7-year life, represents a variation in the annual profit of $\mp\frac{10}{7}\times\frac{200{,}000}{100}=\mp$£2,860, and taking £80/lb. Payload/annum as an average Revenue it is seen that a variation of 36 lb. in payload is equivalent to this variation in cost. Such an accuracy in payload estimation (about 1/10th of one per cent of all-up weight) cannot be expected in a treatment such as this, and hence Amortisation of equipped airframe, power plants and spares, together with Insurance costs, may safely be eliminated when we compare the differences between REVENUE and COST for aeroplanes powered by different types of engine, presented towards the end of this note.

It will be readily appreciated that the turbo-jet aeroplane, lacking propellers and propeller reduction gearing, engine cooling provisions, and so on—with attendant direct and indirect weight penalties—will tend to have a higher ratio of disposable load to all-up weight than comparable piston-engined or turbo-prop aeroplanes. Disposable loads are approximately: —

Piston, 35 per cent—Turbo-prop, 35 per cent—Turbo-jet, 48 per cent of A.U.W. (*c*) and: Piston, 70 per cent —Turbo-prop, 65 per cent—Turbo-jet, 100 per cent of "Basic" Weight (*d*).

["Basic" Weight = Basic operational weight less power plant weight.]

It is evident that, irrespective of the type of engine employed, by and large, the Maintenance and Overhaul costs of the airframe, accessories and equipment may be expected to be about the same per pound of weight thereof per flying hour. On a "per pound of disposable load per annum" basis, therefore, the Maintenance and Overhaul costs will be proportional to the U values in Table I and inversely proportional to the "Basic" weight percentages.

It appears that the Maintenance and Overhaul costs for the power plant, per pound of "Basic" weight per hour, are in the ratio—

$$\text{Piston}:\text{Turbo-prop}:\text{Turbo-jet}=6:4:5^{*}(e)$$

and therefore on a "per pound of disposable load per annum" basis these Maintenance and Overhaul costs will be proportional to the U values in Table I, to the above ratio, and inversely proportional to the

$$\frac{\text{(Disposable load)}}{\text{("Basic" weight)}}$$

percentages given earlier.

Since the number and class of crew is independent of the type of power plant employed, and crew maximum flying hours per annum are fixed by legislation, the Crew Cost per flying hour is constant, and again the cost per lb.

*(*e*) These ratios reflect the differing "Basic" weights of the three kinds of aeroplane; the Maintenance and Overhaul costs per pound of take-off thrust are roughly in the ratio 2:1:1.

of disposable load per annum is proportional to the U value in Table I and inversely proportional to the disposable load percentage of all-up weight.

The number of landings per annum is UV_b/S: all-up weight affects the landing charge, but in a "stepped" manner. Although a much greater fuel load is carried by a turbo-jet aeroplane compared with a turbo-prop or piston-engined one, the lower power plant weight already referred to, compensates for this to a considerable extent and it is fair to neglect any effect of engine type on landing charge per landing per pound of disposable load. Landing cost per pound of disposable load per annum may therefore be taken as proportional to UV_b/S in Table I and inversely proportional to the disposable load percentage.

Thus we have concluded that, per pound of disposable load per annum, the Direct Costs vary as follows:—

Amortisation and Insurance	May be treated as constant.
Maintenance and Overhaul	Airframe, Accessories, Equipment: proportional to U and to one/(disposable load), per cent "Basic" weight. Power plant: ditto, and to the ratio (e) above.
Crew Cost	Proportional to U and to one/(disposable load) per cent A.U.W.
Landing Cost	Proportional to UV_b/S and to one/(disposable load), per cent A.U.W.

The relative fuel consumptions and costs for aeroplanes with the three types of engine, corresponding to the turn-round times used (and hence to the utilisations) in Table I, are found by detailed calculations to be of the general order

TABLE IV

	Consumption/annum	*Cost/gall.*	*Cost per annum. (£)*
Reciprocating-engined	1	7	7
Turbo-prop engined	2	5	10
Turbo-jet engined	5 (any stage distance)	5	25 (any stage distance)

The fuel cost per pound of disposable load per annum is proportional to the values in the last column and inversely proportional to the disposable load percentage.

Indirect Costs

The Indirect Costs, which are not wholly dependent on the characteristics of the aircraft in question, are subject to considerable doubt, as regards magnitude, principal controlling parameter, and so on. Based on the best available information the following ratios of

$$\frac{\text{Total cost} - (\text{Amortisation and Insurance})}{\text{Direct cost} - (\text{Amortisation and Insurance})}$$

are used:—

Stage distance (n.m.)	200	300	500	700	900
Ratio	2·2	2·0	1·8	1·65	1·5

Datum costs

Now assume that, for a turbo-propeller aeroplane in the 30,000 lb. class, the total Direct Operating Cost per hour for a stage length of 500 n.m. is £50, and that the analysis of expenditure is:—

Maintenance and Overhaul	30%	17% Airframe, Access. Equip. 13% Power Plant
Crew Costs	8%	
Landing Costs	5%	
Fuel and Oil	28%	
	71%	
*Amortisation and Insurance	29%	
	100%	

It is again necessary to appeal to the results of detailed calculations; taking the disposable load for the above case as 10,000 lb. the cost per pound of disposable load per annum (less *) is:—

$$\frac{2980\,(a) \times £50 \times 0{\cdot}71}{10{,}000} \simeq £11$$

Per pound of disposable load per annum, therefore, we have for this case:—

Maintenance and Overhaul	£4·66	£2·64 Airframe, Access. Equip. £2·02 Power Plant
Crew Costs	£1·24	
Landing Costs	£0·77	
Fuel and Oil	£4·35	
	=£11·0	

Again using the results of more detailed calculations the following ratios of payload to disposable load are found to obtain with S.B.A.C. (I.F.R.) fuel reserves and allowances in still air:—

TABLE V

Stage distance (n. m.)	200	300	500	700	900
Piston-engined	0·76	0·70	0·60	0·52	0·43
Turbo-prop engined	0·65	0·59	0·48	0·38	0·30 (g)
Turbo-jet engined	0·49	0·44	0·35	0·27	0·19

(Note the reduction of values from top to bottom and from left to right.)

PROFIT

Examples of combining the foregoing figures are now given. The various numbers are identified in the foregoing by the lower case letters, for example "(g)".

Example 1

Turbo-prop aeroplane; 500 n.m. stage.

Revenue per annum per pound of payload (from Table III) £85

Direct Cost per annum per pound of payload

$= \frac{£11}{0{\cdot}48\,(g)} = £23 + (\text{Amortisation and Insurance})$

Total Cost $= £23 \times 1{\cdot}8 = £41{\cdot}4$ ($+ A.$ and $I.$)

Profit per annum per pound of payload

$= £85 - £41{\cdot}4$ ($- A.$ and $I.$) $= £43{\cdot}6$ ($- A.$ and $I.$)

Profit per annum per 10,000 lb. of A.U.W.

$= £43{\cdot}6 \times 10{,}000 \times 0{\cdot}35\,(c) \times 0{\cdot}48\,(g)$

$= £73{,}200$ ($- A.$ and $I.$)

Example 2

Turbo-jet aeroplane; 500 n.m. stage.

Revenue per annum per pound of payload (from Table III) £118

Direct cost per annum per pound of disposable load:—
Maintenance and Overhaul of Airframe, Accessories and Equipment

$$= £2{\cdot}64 \times \frac{2590\,(a)}{2980} \times \frac{65}{100\,(d)} = £1{\cdot}50$$

Maintenance and Overhaul of Power Plant

$$= £2.02 \times \frac{2590\,(a)}{2980} \times \frac{5}{4}\,(e) \times \frac{65}{100\,(d)} = £1{\cdot}42$$

Crew Costs

$$= £1{\cdot}24 \times \frac{2590\,(a)}{2980} \times \frac{0{\cdot}35}{0{\cdot}48\,(c)} = £0{\cdot}79$$

Landing Costs

$$= £0{\cdot}77 \times \frac{1570\,(b)}{1132} \times \frac{0{\cdot}35}{0{\cdot}48\,(c)} = £0{\cdot}78$$

Fuel and Oil

$$= £4{\cdot}35 \times \frac{25\,(f)}{10} \times \frac{0{\cdot}35}{0{\cdot}48\,(c)} = £7{\cdot}95$$

$$= £12{\cdot}44 + (A.\text{ and }I.)$$

Direct Cost per annum per pound of payload

$$= \frac{£12{\cdot}44}{0{\cdot}35\,(g)} = £35{\cdot}6$$

Total Cost

$$= £35{\cdot}6 \times 1{\cdot}8 = £64{\cdot}1\,(+A.\text{ and }I.)$$

Profit per annum per pound of payload

$$= £118 - £64{\cdot}1\,(-A.\text{ and }I.) = £53{\cdot}9\,(-A.\text{ and }I.)$$

Profit per annum for 10,000 lb. of A.U.W.

$$= £53{\cdot}9 \times 10{,}000 \times 0{\cdot}48\,(c) \times 0{\cdot}35\,(g)$$

$$= £90{,}700\,(-A.\text{ and }I.)$$

The result of all such Profit* calculations for the cases considered are as follows:—

TABLE VI

Stage distance (n.m.)	200	300	500	700	900
Piston-engined	£96,000	£86,000	£75,000	£59,500	£42,500
Turbo-prop engined	£96,000	£87,000	£73,000	£49,000	£29,500
Turbo-jet engined	£108,000	£101,000	£91,000	£57,000	£20,500

*Amortisation and Insurance costs have, for the reason given on page 561, not been deducted from the Revenue; only the difference between the figures in Table VI are therefore significant, but subject to the qualification mentioned at the beginning.

The Direct Operating Costs (less Amortisation and Insurance) inherent the foregoing are as follows (£/1 lb. payload/nautical mile $\times 10^3$):—

Stage distance (n. m.)	200	300	500	700	900
Piston-engined	3·80	3·62	3·76	4·23	4·85
Turbo-prop engined	3·95	3·81	4·05	4·70	5·70
Turbo-jet engined	4·60	4·40	4·57	5·37	7·17

OTHER RELATIVE PROPERTIES

The load-shifting ability of the types considered is:—
Ton miles per annum per 10,000 lb. of A.U.W.

$$= \left(\frac{10{,}000}{2240}\right) \times UV_b \times \left(\frac{\text{Disposable load}}{\text{A.U.W.}}\right)(c) \times \times \left(\frac{\text{Payload}}{\text{Disposable load}}\right)(g)$$

$(= 4{\cdot}46)$

and the values are as follows:—

TABLE VII

Stage distance (n. m.)	200	300	500	700	900
Piston-engined	440,000	440,000	420,000	385,000	326,000
Turbo-prop engined	460,000	460,000	430,000	370,000	300,000
Turbo-jet engined	610,000	610,000	590,000	495,000	370,000

The frequency of the service provided when a fleet of aeroplanes performs a given number of passenger- or ton-miles of work per annum is proportional to the number of landings per annum per aeroplane divided by the passenger- or ton-miles per annum per aeroplane; corresponding to the values in Tables I and VII, the relative values are as follows:—

TABLE VIII

Stage Distance (n. m.)	200	300	500	700	900
Piston-engined	411	297	208	171	162
Turbo-prop engined	485	355	264	234	233
Turbo-jet engined	475	356	266	248	272

It will be noted that, on this score, the turbo-jet aeroplane shows up best for all except the shortest stage distance covered, in which case the turbo-prop has a slight advantage.

CONCLUSION

It is apparent, from the figures in Tables VI, VII and VIII, that a turbo-jet aeroplane is a sound proposition for short-haul operations; profit-wise the best of the three types depends on the representative stage length, but in the load-shifting ability the turbo-jet is clearly superior. For a given work-rate, the frequency of service provided by the piston-engined aeroplane is distinctly lower than for the turbo-prop and turbo-jet aeroplanes.

The Vibrations of Laced Turbine Blades

by

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FREQUENCY equations of fairly simple form are derived for the modes of vibration of turbine blades laced at their tips. These equations are discussed and are presented in such a manner that recently published Vibration Analysis Tables may be used.

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INTRODUCTION

While the use of blade lacing wires or shrouding is not altogether common in gas turbine practice, occasions may arise when their use is desirable, and the purpose of this note is to present a method whereby the vibrational characteristics of a number of blades wired together may be conveniently found.

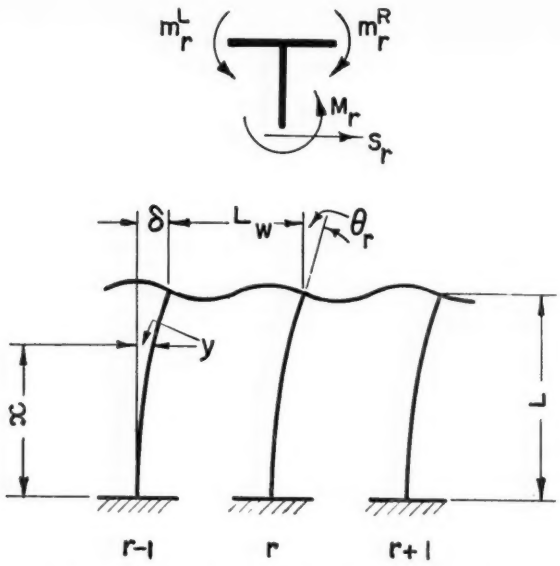


FIGURE 1. The vibrations of laced turbine blades.

Analyses do exist whereby the fundamental frequency only of a large number of laced blades may be found by energy methods[1, 2], while Smith[3] has derived a frequency equation for a general number of blades in the form of a determinant with transcendental elements. This determinant is of the order $(n+1)$, where n is the number of blades, and obviously the computational work involved is extensive.

However, as will be shown, Smith's equations may be put in a very reasonable form by using the methods of the Calculus of Finite Differences. The labour in solving the resultant characteristic equations has been even further reduced by the recently published set of "Vibration Analysis Tables" by Bishop and Johnson[4], which contain tables of a large number of the transcendental functions arising from the equations governing the flexural oscillations of uniform beams.

ASSUMPTIONS

In dealing with the vibrations of laced blades, it is usual to make several assumptions, as follows:—

(*i*) The blading is replaced by a set of uniform parallel blades, fixed at their roots, each vibrating in a plane perpendicular to their least principal axes, the lacing wire connecting the blade tips lying in the plane of motion. Obviously this neglects the obliquity of the blading and the resultant coupling due to the wire not lying along a principal plane of the blade, but the effect seems to be small[2].

(*ii*) The lacing wire, which is regarded as inextensible and maintaining a constant tip pitch, is taken as a set of masses concentrated at the blade tips, thereby neglecting the transverse motion of the wire. However, the mass of the wire and its amplitude of transverse motion will be small compared with that of the blade so again the effect should be negligible.

(*iii*) The stiffening and coupling effects of centrifugal forces are neglected. This is reasonable for the higher modes of vibration of short blades on large diameter discs, but the root tightening effect of rotation is implicit in (*i*) where rigid root fixings are assumed.

THE DIFFERENCE EQUATIONS

Considering a blade of length L, weight per unit length w and flexural rigidity EI, the deflection y at a distance x from the root when vibrating at a natural circular frequency ω is

$$y = A\cos\lambda x + B\sin\lambda x + C\cosh\lambda x + D\sinh\lambda x \qquad (1)$$

where $$\lambda^4 = w\omega^2/(gEI) \qquad (2)$$

Now at $x=0,\ y=y'=0$

so that $A=-C$ and $B=-D$.

The bending moment and shear force at x are then given by $EI\,(d^2y/dx^2)$ and $EI\,(d^3y/dx^3)$ respectively. Then if δ, θ, M and S are the deflection, slope, moment and shear force respectively at the blade tip, all positive as shown in Fig. 1, these relationships can be combined to give

$$\frac{M}{\lambda^2 EI} = \frac{(\sin\lambda L\sinh\lambda L)\,\delta + (\cos\lambda L\sinh\lambda L - \sin\lambda L\cosh\lambda L)\,\theta/\lambda}{(\cos\lambda L\cosh\lambda L - 1)}$$

and

$$\frac{S}{\lambda^3 EI} = \frac{(\sin\lambda L\cosh L + \cos\lambda L\sinh\lambda L)\delta - (\sin\lambda L\sinh\lambda L)\theta/\lambda}{(\cos\lambda L\cosh\lambda L - 1)}$$

or using the notation of Ref. 4,

$$\frac{M}{\lambda^2 EI} = \frac{F_1}{F_3}\delta + \frac{F_5}{F_3}\frac{\theta}{\lambda} \qquad (3)$$

and

$$\frac{S}{\lambda^3 EI} = \frac{F_6}{F_3}\delta - \frac{F_1}{F_3}\frac{\theta}{\lambda} \qquad (4)$$

the F_i being tabulated functions.

The static equations of bending apply to the lacing wire, and referring to Fig. 1, the bending moments applied by the wire to the left and right of the r^{th} blade are,

$$m_r^L = (E_w I_w/L_w)\,(4\theta_r + 2\theta_{r-1})$$

and

$$m_r^R = -(E_w I_w/L_w)\,(4\theta_r + 2\theta_{r+1}) \qquad (5)$$

Now for equilibrium at the r^{th} joint shown, the algebraic sum of the bending moments there is zero, or,

$$M_r + m_r^L - m_r^R = 0$$

on using equations (3) and (5),

$$\lambda^2 EI\left(\frac{F_1}{F_3}\delta + \frac{F_5}{F_3}\frac{\theta_r}{\lambda}\right) + \frac{E_w I_w}{L_w}(2\theta_{r+1} + 8\theta_r + 2\theta_{r-1}) = 0$$

or,

$$\theta_{r+1} + \left(4 + K\frac{\lambda L}{2}\frac{F_5}{F_3}\right)\theta_r + \theta_{r-1} = -K\frac{(\lambda L)^2}{2}\frac{F_1}{F_3}\left(\frac{\delta}{L}\right) \qquad (6)$$

where K is the stiffness ratio of blading to wire,

$$K = \frac{EI}{L}\cdot\frac{L_w}{E_w I_w} \qquad (7)$$

Equation (6) is a non-homogenous, second-order linear difference equation[5], and as in the case of linear differential equations the solution will consist of a primitive

satisfying the homogenous equation, together with a particular solution satisfying the whole equation.

For the primitive or complementary solution assume,

$$\theta_r = (-1)^r P \exp(\phi r)$$

where P is a disposable constant and ϕ is to be determined. Substitution in equation (6) gives

$$0 = \exp(\phi) - \left(4 + K\frac{\lambda L}{2}\frac{F_5}{F_3}\right) + \exp(-\phi)$$

or

$$\cosh\phi = \left(2 + K\frac{\lambda L}{4}\frac{F_5}{F_3}\right) \quad . \quad . \quad (8)$$

This is the characteristic equation giving two roots $\pm\phi$, so that the complementary solution is

$$\theta_r = (-1)^r (P\cosh\phi r + Q\sinh\phi r) \, . \quad . \quad (9)$$

The particular solution is readily seen to be a constant, $\theta_r = \Theta$, substitution in equation (6) giving

$$\Theta = -K\frac{(\lambda L)^2}{2}\frac{F_1}{F_3}\left(\frac{\delta}{L}\right) \Big/ \left(6 + K\frac{\lambda L}{2}\frac{F_5}{F_3}\right) \quad (10)$$

$$= -\frac{K(\lambda L)^2}{4(1+\cosh\phi)}\frac{F_1}{F_3}\left(\frac{\delta}{L}\right).$$

The complete or general solution is then the sum of equations (9) and (10).

Now examination of the graph of $\lambda L F_5/F_3$, Fig. 2, shows values ranging from ∞ to $-\infty$. Consequently it is necessary to examine over what ranges of λL the above solution is valid. From the characteristic equation the above solution holds provided that

$$\left(2 + K\frac{\lambda L}{4}\frac{F_5}{F_3}\right) > 1, \text{ or } \lambda L\frac{F_5}{F_3} > -\frac{4}{K}$$

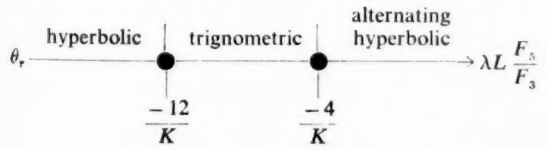
The solution will also hold if ϕ is allowed to be imaginary, in which case $\cosh\phi$ lies in the range -1 to $+1$

$$\text{or } -1 < \left(2 + K\frac{\lambda L}{4}\frac{F_5}{F_3}\right) < 1, \text{ or } -\frac{12}{K} < \lambda L\frac{F_5}{F_3} < -\frac{4}{K}$$

If $\cosh\phi$ is less than -1, a new solution must be taken, $\theta_r = P\exp(\phi r)$, this is necessary when

$$\left(2 + K\frac{\lambda L}{4}\frac{F_5}{F_3}\right) < -1 \text{ or } \lambda L\frac{F_5}{F_3} < -\frac{12}{K}$$

These results may be summarised as follows,



Special attention must be given to the values of $\cosh\phi = 1$ or -1, since the characteristic equation then has double roots, 0 or $i\pi$. Proceeding in a manner similar to that used in differential equations the corresponding solutions are

$$\theta_r = (-1)^r(A + Br) - \frac{K(\lambda L)^2}{8} \cdot \frac{F_1}{F_3}\left(\frac{\delta}{L}\right), \ \phi = 0$$

and

$$\theta_r = (A + Br) - \frac{K(\lambda L)^2}{4}\frac{F_1}{F_3}\left(\frac{\delta}{L}\right) r^2, \ \phi = i\pi \quad . \quad (11)$$

Having obtained these general solutions the appropriate boundary conditions can be fitted to obtain the frequency equations and modes of vibrations.

THE FREQUENCY EQUATIONS

For ease in discussing the results to be obtained a packet of blading with an odd number of blades, $(2N+1)$, will be considered. This allows an origin to be taken at the centre of the blading so that symmetric and asymmetric modes may be considered separately.

(*a*) *Symmetric modes*

Considering firstly the symmetric modes there will be no sideway or longitudinal displacement of the lacing wire, and the slope at the origin, or centre blade, will be zero. The general equations (9) and (10) then give,

$$\theta_r = (-)^r Q \sinh\phi r \quad . \quad . \quad . \quad (12)$$

Equilibrium of the moments at the tip of the end blade, $r = N$, demands,

$$m_N{}^L + M_N = 0.$$

Substitution from equations (3) and (5) gives,

$$0 = \theta_{N-1} + \left(2 + \frac{K\lambda L}{2}\frac{F_5}{F_3}\right)\theta_N$$

$$= \theta_{N-1} + 2(\cosh\phi - 1)\,\theta_N$$

$$= \sinh\phi\,(N+1) - 2\sinh\phi N \, . \quad . \quad (13)$$

This is the frequency equation, and rejecting the root $\phi = 0$ there is seen to be one real root, and $(N-1)$ imaginary roots.

For moderate values of N, calculations and discussion may be much simplified by a further assumption. On taking the end spans of the lacing wire twice as stiff as the other spans the above equilibrium equation becomes

$$0 = \theta_{N-1} + \left(2 + \frac{K\lambda L}{4}\frac{F_5}{F_3}\right)\theta_N$$

$$= \sinh\phi\cosh\phi N \quad . \quad . \quad . \quad (14)$$

Again rejecting the root $\phi = 0$, in this case there are no real roots, and obviously

$$\phi_N = i(p + \tfrac{1}{2})\pi$$

where p is an integer.

Thus, from equation (8) the frequencies of the symmetric modes of vibration may be solved from

$$\lambda L\frac{F_5}{F_3} = -\frac{4}{K}\{2 - \cos[(p+\tfrac{1}{2})\pi/N]\} \quad . \quad (15)$$

Permissible values of p are 0, 1, 2 . . . $(N-1)$, the values $p = N$, $(N+1)$ . . . and so on, merely repeating the values of ϕ given by $p = (N-1)$, $(N-2)$ . . . and so on.

Two very obvious conclusions may be drawn from equation (13): when K, the ratio of blade to wire stiffness is very large then $F_5 = (\cos\lambda L\sinh\lambda L - \sin\lambda L\cosh\lambda L)$ must tend to zero, indicating that each blade will vibrate at frequencies given by $F_5 = 0$, or at the frequencies of a blade clamped at one end and hinged at the other end. Similarly when the wire is infinitely rigid K, and hence $F_3 = (\cos\lambda L\cosh\lambda L - 1)$ must be zero, this representing the blade clamped at each end.

For intermediate values of K, inspection of Fig. 2 shows that $\lambda L F_5/F_3$ has an infinite number of branches, hence the frequency spectrum for the symmetric modes consists of an infinite number of bands of modes, there being N modes in each band corresponding with the values of p given above.

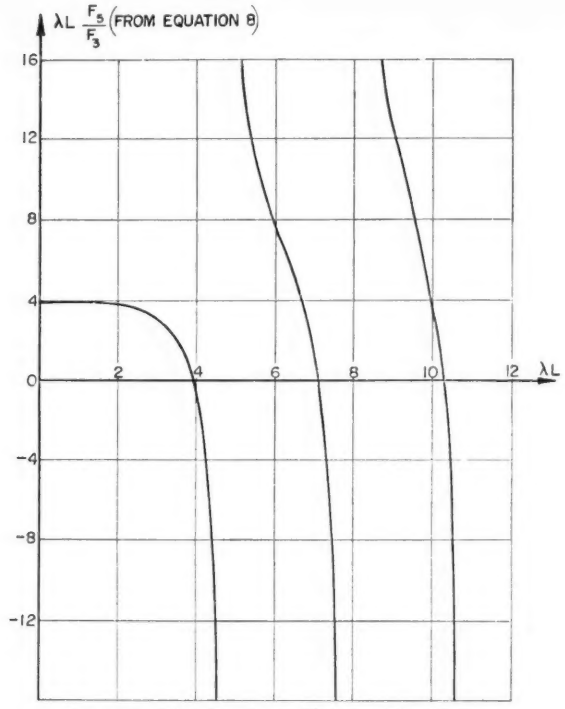


FIGURE 2. The vibrations of laced turbine blades.

Typical values of K will be greater than say 50, and thus $\lambda L F_5/F_3$ will probably lie in the range 0 to $-0{\cdot}25$. The modes in any one band will thus have frequencies very near to each other, these frequencies approaching closely to the frequency of a clamped-pinned blade. In addition, due to the assumption concerning the lacing wire mass distribution, these frequencies are not influenced by the mass of the wire.

(*b*) *Asymmetric modes*

In the asymmetric modes of vibration there is a longitudinal displacement of the lacing wire, but the slopes at the tips of the blades on either side of the centre line will be equal, or,

$$\theta_1 = \theta_{-1}.$$

Thus, from equations (9) and (10) noting that $\sinh \phi \neq 0$,

$$Q = 0.$$

As in the previous case the equilibrium equation at the tip of the N^{th} blade is

$$0 = \theta_{N-1} + 2(\cosh \phi - 1)\theta_N$$
$$= \Theta(2\cosh \phi - 1) + P(-1)^N [\cosh \phi (N+1) - 2\cosh \phi N] \quad . \quad . \quad . \quad (16)$$

Then, if W_w is the total weight of the lacing wire which has a longitudinal oscillation of amplitude δ and circular frequency ω, the sum of the shear forces at the blade tips must equal the mass of the wire multiplied by its acceleration, or,

$$\sum_{-N}^{N} S_r = -\frac{W_w}{g}\omega^2\delta$$

Using equations (2) and (4) this becomes,

$$(2N+1)\frac{F_6}{F_3}\delta - \frac{F_1}{\lambda F_3}\Sigma\theta_r = -\frac{W_w}{w}\lambda\delta$$

Writing W for the ratio of the weight of the wire to the total weight of the blading,

$$W = \frac{W_w}{(2N+1)wL} \quad . \quad . \quad . \quad (17)$$

and re-arranging the above equation

$$\Sigma\theta_r = (2N+1)\left[\lambda L\frac{F_6}{F_1} + (\lambda L)^2 W\frac{F_3}{F_1}\right]\left(\frac{\delta}{L}\right)$$

Now, using equations (9) and (10),

$$(2N+1)\Theta + P\sum_{-N}^{N}(-1)^r\cosh \phi r =$$
$$= \frac{-4(2N+1)}{K}\left(\frac{F_3F_6}{\lambda LF_1^2} + W\frac{F_3^2}{F_1^2}\right)(1+\cosh\phi)\Theta.$$

Writing $$\Omega = \left(\frac{F_3F_6}{\lambda LF_1^2} + W\frac{F_3^2}{F_1^2}\right) \quad . \quad . \quad (18)$$

and then carrying out the summation the above equation becomes

$$0 = \Theta(2N+1)\left[1 + \frac{4\Omega}{K}(1+\cosh\phi)\right] +$$
$$+ P(-1)^N\frac{[\cosh\phi(N+1) + \cosh\phi N]}{(1+\cosh\phi)} \quad (19)$$

Elimination of Θ and P from (14) and (17) then yields the frequency equation.

The device used in the previous section of imagining the end spans of the lacing wire to be stiffened up may again be used with advantage. Equation (14) now becomes

$$0 = \Theta(1+\cosh\phi) + P(-1)^N\sinh\phi\sinh\phi N$$

and the frequency equation is,

$$0 = (2N+1)[1 + (4\Omega/K)(1+\cosh\phi)]\sinh\phi\sinh\phi N -$$
$$- [\cosh\phi(N+1) + \cosh\phi N] \quad . \quad (20)$$

Now considering the range where the wire stiffness is small, or K has fairly large values, then from equation (8), and the discussion in the previous section, then if ϕ is real its value can be expected to be large. The hyperbolic terms in the frequency equation may then be replaced by exponential terms and writing $\cosh\phi \simeq \sinh\phi \simeq \frac{1}{2}\exp(\phi)$, and so on, the above equation becomes

$$0 = (2N+1)[1 + (4\Omega/K)(1+\cosh\phi)] - 2[1+\exp(-\phi)]$$

Thus if $(2N+1)$ is large the first term must tend to zero, or using equation (8) and noting K is large

$$0 = 1 + \frac{4\Omega}{K}\left(3 + K\frac{\lambda L}{4}\frac{F_5}{F_3}\right) = 1 + \Omega\lambda L\frac{F_5}{F_3}$$
$$= F_1^2 + F_5F_6 + W\lambda LF_3F_5.$$

Substitution from equations (3) and (4) then gives after reduction

$$0 = (\cos\lambda L\cosh\lambda L + 1) + W\lambda L(\cos\lambda L\sinh\lambda L -$$
$$- \sin\lambda L\cosh\lambda L) \quad (21)$$

This is the frequency equation for an end-loaded cantilever, and resembles the fundamental mode of the packet, providing either a convenient approximation, or a close starting point for trial and error calculations, for the true frequencies of the packet.

In a similar manner, if K tends to zero, then ϕ, if real, will have a finite value, so that in equation (20) above Ω must also tend to zero. Thus, from equation (18),

$$0 = F_6 + W\lambda L F_3$$

$$= (\cos \lambda L \sinh \lambda L + \sin \lambda L \cosh \lambda L) + W\lambda L (\cos \lambda L \cosh \lambda L - 1) \quad . \quad (22)$$

This equation yields the frequencies of an end-loaded blade clamped at one end, and direction-fixed, corresponding with a large stiffness of wire, but position-free at the other end. The roots of this equation can of course be read off from a graph of the above functions where it will be seen that changes in W have a significant effect on the frequency of the higher modes.

Supposing now that some of the roots of the frequency equation (20) are imaginary, then taking $(2N+1)$ as fairly large and noting that the right-hand term will be less than two then,

$$0 = [1 + (4\Omega/K)(1 + \cosh \phi)] \sinh \phi \sinh \phi N \quad (23)$$

The case of the term in braces being zero has just been shown to yield real roots, so on rejecting the special case $\phi = 0$, equation (23) has roots given by $\sinh \phi N = 0$ or, $\phi N = ip\pi$, p integral and from equation (8)

$$\lambda L \frac{F_5}{F_3} = -\frac{4}{K}[2 - \cos(p\pi/N)] \quad . \quad (24)$$

permissible values of p being 1, 2 . . . $(N-1)$.

Comparing this result with equation (15), it can be seen that there are bands of asymmetric modes whose frequencies lie within the bands of symmetric modes previously discussed. In practical cases these frequencies will almost coincide and it is obvious that there will be little longitudinal displacement of the lacing wire, and that the mass of the wire will have only a negligible effect on the frequency of this band.

The frequency spectrum thus consists of an infinite number of modes closely akin to the modes of an end-loaded cantilever, these modes being interspaced by bands containing $(N-1)$ modes akin to the clamped-pinned blade.

CONCLUSIONS

The frequency equations for the symmetric and asymmetric modes of vibration of a packet of laced turbine blades have been derived and discussed. The frequencies have been shown to consist of a series of modes corresponding to the fundamental and overtones of an end-loaded cantilever, these frequencies being interspaced by bands of modes with little or no displacement of the lacing wire.

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Note on an Improved Short-Cut Method for Estimating Aircraft Direct Operating Costs

by

FRANK ROBERTSON, A.F.R.Ae.S.

IT SHOULD be remembered that the method outlined herein refers always to *STILL AIR*. If a particular stage, such as the North Atlantic, is being analysed, then the block distance must be increased by an amount derived from the prevailing wind speed and aircraft cruising speed before an E.S.A. range is read off from Fig. 3.

INTRODUCTION

In the early stages of preliminary design, it is essential to have a method for the comparison of aircraft on an operating cost basis. The standard S.B.A.C. method is too lengthy and, in any case, demands a greater amount of data than is usually available in the early design stages.

The formula presented in this note is an extension to the ones presented by the author in the January 1955 and November 1956 JOURNALS and is more accurate in that it provides for variation in aircraft first cost, type of power plant, speed and range.

It is submitted that the formula gives a reasonable first estimate, suitable for early design comparisons, and that the few parameters required are normally available at the earliest stage of the design.

Received 27th April 1957.

DISCUSSION

An empirical formula does not need to be logical nor need it have a scientific or mathematical theory behind it.

To be of any real value, however, it must give approximately the right answer; it must be easy to remember and capable of rapid application.

The formula published by the author in November 1956 :—

$$\left(C = \frac{1000\,W}{VP} + \frac{10{,}000\,F}{PR}\right)$$

gives approximately the right answer for long range aircraft or for medium range *slow* aircraft, provided that their first cost is round about £9/lb.W.

It tends to be too inaccurate to be of value for short range aircraft and for medium range *fast* aircraft and it does not provide for variation in first cost and annual utilisation.

Bearing these shortcomings in mind, the author has evolved a new formula which is much more accurate over a wider range and does not involve any additional data.

Charts are provided which allow factors to be read off to cover such items as varying first cost and utilisation,

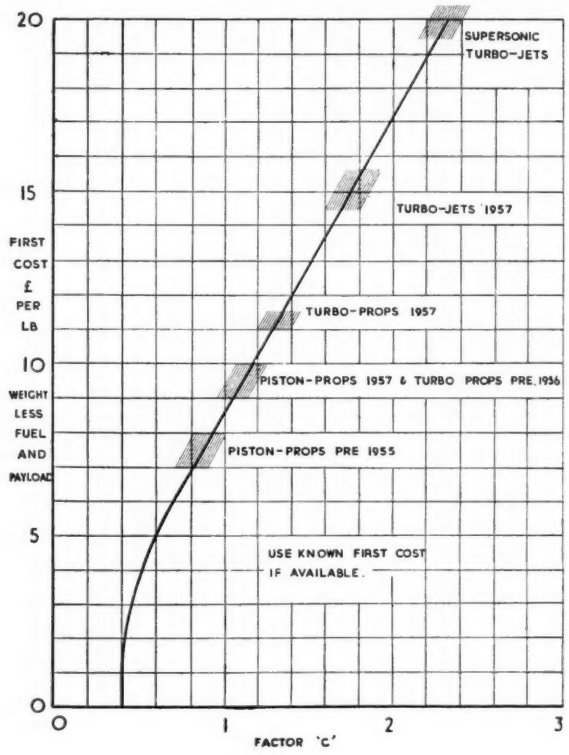

FIGURE 1.

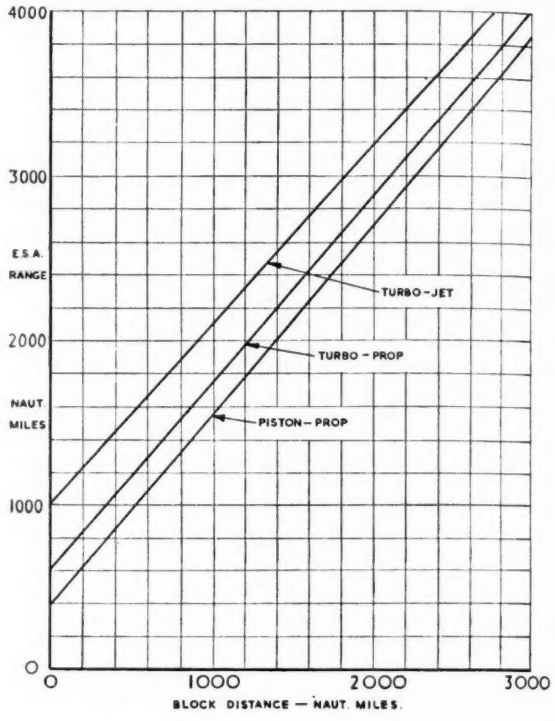

FIGURE 3.

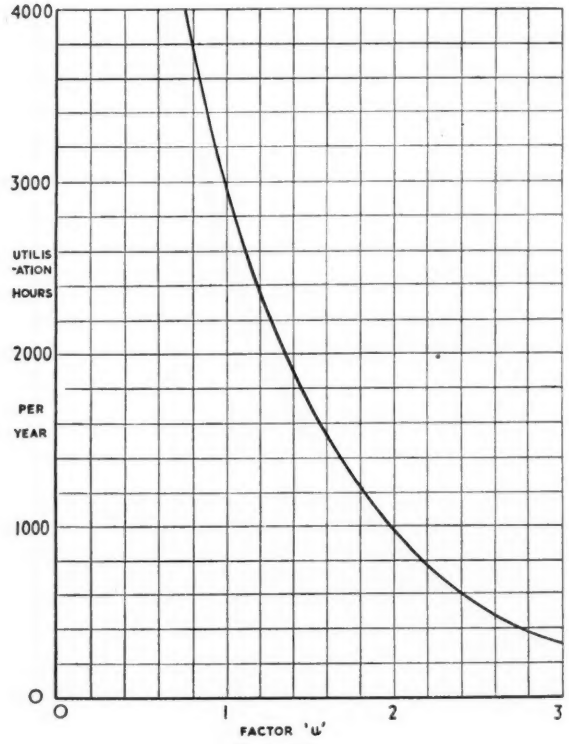

FIGURE 2.

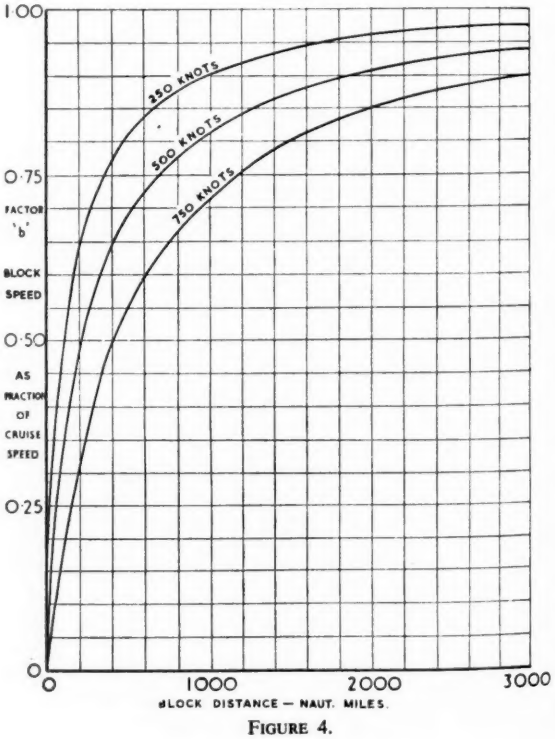

FIGURE 4.

the relationship between block distance and E.S.A. range and that between block speed and cruising speed.

Checks have been made with the full S.B.A.C. method on a variety of designs and the formula seems to be accurate to within about 10 per cent.

DATA REQUIRED

All-up weight of aircraft.
Type of power plant.
Weight of aircraft, less fuel and payload in lb.
True mean cruising speed of aircraft in knots.
Capacity payload in lb.
Capacity fuel in lb.
Equivalent still air range with capacity fuel in nautical miles.

FORMULA

$$C = \frac{1000\,cuW}{VbP} + \frac{10{,}000\,F}{PR}$$

where C operating cost at $\frac{3}{4}$ load factor in pence per long ton nautical mile
c first cost factor—read from Fig. 1
u utilisation factor—read from Fig. 2 (having decided upon an annual value)
W aircraft weight, less fuel and payload, in lb.
V mean cruising speed in knots
b block speed factor—read from Figs. 3 and 4
P payload carried in lb.
F fuel carried in lb.
R equivalent still air range with fuel F in nautical miles

NOTES ON USE OF FORMULA

1. Collect data required as listed.
2. Decide block distance.
3. From Fig. 3 read off E.S.A. range (R).
4. From data, calculate fuel required (F).
5. From data, calculate payload carried (P).
6. From Fig. 1, read off first cost factor (c).
7. By roughing out time-table or from statistics, decide upon annual utilisation.
8. From Fig. 2, read off utilisation factor (u).
9. From Fig. 4, read off block speed factor (b).
10. Apply formula.

SPECIAL NOTE

Aircraft required to operate continuously at altitudes below about 20,000 ft. and at the same time at true speeds above about 350 knots need special treatment for block distances below about 1,000 nautical miles.

Graduates' and Students' Section

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The Graduates' and Students' Section Committee for 1957/58 was elected on 2nd July and is:—

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Hon. Visits Secretary—R. Shepherd (*Graduate*), de Havilland Aircraft Co. Ltd., Technical Assistant, Stress Office.

Hon. Editor—P. T. Ross* (*Graduate*), B.E.A., Performance Engineer.

Members—N. K. Benson (*Graduate*), Handley Page Ltd., Stressman; M. P. Laker (*Student*), late Queen Mary's College, London University; A. R. M. Pickering* (*Student*), Vickers-Armstrongs (Aircraft) Ltd, Undergraduate Apprentice; L. H. Pretty* (*Student*), Imperial College, Student.

* indicates new committee member.

THE SUMMER PARTY

The following letter has been received:—

Sir,

I was present at the party on 21st June, and despite the pleasant weather and satisfying refreshments, I cannot help feeling that the evening did not go quite as well as had been hoped.

A party it was called, and a party it was most certainly not. It is true that the last minute defection of the promised Skiffle Group was unforeseeable, but there was lacking just the little organisation which would have kept things going.

May I suggest that if the Summer Dance is to be retained as a party there should be a lively M.C., and actual records (or a Skiffle Group) instead of a tape recording, which is too inflexible. The evening should be kept informal and the party spirit fostered. If not, then the date could be kept as a formal dance similar to that held in the winter.

"GRADUATE."

[The Committee would be glad to have further comments and suggestions on the Summer Party to help plan future occasions: they would particularly like to know if you would prefer to keep the informal atmosphere.—*Hon. Ed.*]

VISIT TO THE R.A.E. ROCKET PROPULSION DEPARTMENT, WESTCOTT

A DULL DAY failed to damp the enthusiasm of the twenty-eight members of the section who visited Westcott on 10th July.

After an introductory talk the first demonstration of the programme consisted of the inspection of a large solid-fuel rocket motor. The significance of a hooter and various red and yellow flags was explained and the party retreated to a safe distance to witness the firing. This was most impressive.

An instructive and extremely entertaining demonstration of the chemical properties of fuels and oxidants followed. Spectacular "bangs and flashes" staged in one of the laboratories proved beyond doubt the potentialities and dangers involved in working with such materials.

The next item in the programme proved to consist of a film of the firing of an experimental liquid-fuel motor. Having seen this, a visit was made to watch the static firing of a test liquid-fuel engine. One particularly interesting feature was the observation of the shock pattern produced in the efflux.

The museum of German rocket motor development was next inspected. The exhibits here emphasised the immense lead which the Germans had established in this field some thirteen years ago. Several of the more familiar weapons such as the V.1 and V.2 missiles were represented and among the perhaps lesser known items the Messerschmitt Rocket Interceptor and other anti-bomber weapons featured prominently. One suspects that the enemy production effort had been spread too thinly over too many projects when the diversity of the exhibits is studied. The only non-German item on show was a Japanese piloted glider bomb; this was provided with controls so that after launching from the parent aircraft the pilot could sight on his target and dive—but not pull out! Throughout the museum the workmanship on the exhibits was seen to be of the highest standard which was remarkable in view of the extremely short working life required.

The visit concluded pleasantly with tea, and one was left with the impression of a visit of great interest, during which much was learnt but a great deal more necessarily left unseen.

As on previous visits to Ministry of Supply Establishments, the organisation throughout was most commendable and our gratitude is due to the Chief Superintendent of Westcott for granting permission for the visit and to all those (particularly Lt.-Commander Hull) who so capably demonstrated and lucidly explained, throughout the programme.—R.S.

THE LIBRARY

Reviews

RELAXATION METHODS IN THEORETICAL PHYSICS, VOL. II. *R. V. Southwell. Clarendon Press, Oxford, 1956. 273 pp. Illustrated. 55s.*

In 1935 there appeared in the Proceedings of the Royal Society a short paper describing a new but apparently highly specialised numerical method. Its object was specifically to enable stress calculations for redundant frameworks to be made, without the necessity of solving sets of simultaneous algebraic equations, and the author directed his attention particularly to braced frameworks. He gave to his process the name of "The Method of Systematic Relaxation of Constraints." As it grew up in later years the process came to be known, as many children do, by a shorter form of its given name, and Sir Richard Southwell is rightly and widely known today as the father of "Relaxation." Few fathers have spent their time so assiduously on behalf of their offsprings, and of even fewer can it be said that their efforts have met with such success. In 1940 and again in 1946 Sir Richard published two volumes which may be regarded as progress reports of the then youthful Relaxation. If we now regard the 1940 volume as showing the somewhat laboured touch of inexperience the 1946 volume certainly promised a rich versatility—a promise which has been amply fulfilled in Southwell's third volume, now published to coincide almost exactly with the twenty-first birthday of the original paper.

After reading this third volume the thought occurred that a comparison with the paper of 1935 might be of interest. It was with some surprise that a one-page section in that paper was discovered, headed "General Outline of the Method." It comprises a masterly and simple description of the basic idea from which Relaxation has grown. Southwell himself could scarcely have anticipated even a fraction of the development which has matured from that first brief "General Outline," yet it still remains the guiding principle of his work and it remains as true and as illuminating today as when it was written; the philosophy which it proclaims has never been out of Sir Richard's mind and is the seed from which his latest volume has evolved.

The versatility of Southwell's development of the Relaxation Method cannot be better illustrated than by quoting from the list of topics and problems which he tackles in the book now under review—slow motion of a viscous fluid, flexure of a plate, stresses in a tension-member, stresses in artillery shells, modes of resonance in a Klystron tube, elastic stability of a plate-cantilever, buckling of a circular plate, plastic distortion of a tension-specimen. In all, the book includes the solution of twenty-seven problems of a wide variety of physical and engineering interest. Together with the thirty-five solutions which illustrate the 1946 volume they form an impressive list.

The book is produced according to the usual high standards of the Oxford University Press, particularly to be commended being the many and detailed diagrams which are a familiar characteristic of Relaxation. The book forms a direct continuation of the 1946 volume, chapter, page and figure numbers following consecutively on from that earlier work. The methods of the earlier book are extended logically so as to deal with more advanced problems; briefly, the first volume concerned itself basically with problems governed by second order partial differential equations (*e.g.* Poisson's equation), while the new volume deals with fourth order equations (*e.g.* the biharmonic equation). In addition, many readers will be pleased to find an account of some applications of Relaxation to non-linear problems. The author rightly recognises that all such problems are intricate from any point-of-view and points out that each non-linear problem may call for an individual special device to render it tractable. A description of a number of these special devices should be sufficient to encourage computers to tackle other non-linear problems. They may well have to develop new devices, but, after studying Sir Richard's books, they should have acquired a facility to apply their imagination along promising or hopeful lines; they will not always be successful, but the example is now provided for them to embark in a spirit of adventure rather than mere bravado. The latest book is recommended to all whose work concerns the application of mathematics to the theoretical solution of particular problems in Engineering and Physics. Together with the earlier, 1946, volume it forms a reference work to Relaxation Methods of the greatest value.—D. N. DE G. ALLEN.

THE PROBLEMS OF VISION IN FLIGHT AT HIGH ALTITUDE. *Thomas C. D. Whiteside. AGARDograph 13. Butterworths Scientific Publications, London, 1957. 162 pp. Illustrated. 35s.*

The problems of vision at high altitude have been investigated from both the physical and physiological aspects which collectively are interpreted by the subject in terms of visual haze.

By experimental work in the air and on the ground the author has provided data which has collated and amplified much that was previously held on purely subjective evidence.

In the first three sections, an account is given of the historical background and the three most likely causes for subjective visual haze—namely light intensity and contrast, intraocular fluorescence and intraocular scatter.

The subsequent chapters are devoted to physiological factors. Those affecting visibility inside and outside the cockpit are discussed, but the greater part is concerned with altitude myopia and the experiments devised to estimate the amount of accommodation which is exerted involuntarily in an empty visual field. Objectively, the accommodation was assessed by photographing and measuring the third Purkinje-Sanson image, *i.e.* that reflected from the anterior surface of the human lens. The technique is described. The author judges this myopia to be of the order of 0·50 to 1·00 Dioptre and that "slightly long-sighted people are better at search both in an empty visual field and where detail is present, than are normally sighted or short-sighted subjects." In the last war this contention was strikingly proved in practice by the high correlation which obtained between the visual acuity of pilots and their aerial successes.

This publication, sponsored by A.G.A.R.D., is well printed and produced and there are five pages of references; it forms an instructive contribution to visual problems at high altitude for all who have to do with flight in the stratosphere or, in what the author calls the world above the world.—J. C. NEELY.

GLOBAL STRATEGY. *E. J. Kingston-McCloughry. Jonathan Cape, London, 1957. 270 pp. 18s.*

For anyone to attempt to analyse and discuss the global strategy of the present day world in one volume of some 260 pages argues a great deal of courage. The author of this book certainly possesses that courage, as his war-time record shows. But it is likely that now the volume is launched he might well be considering a follow-up of at least two volumes of the same size, which will not show the signs of haste and pressure that are very clear in the present book.

Global strategy to-day is an immense subject. It is not merely the story of Russia versus America in the field of the cold war, with occasional excursions into the hot war of Korea and Indo-China. It is the relation in military matters between the ideologies of a number of great Western powers—of the Russian bloc—a bloc or block that is showing some sinister looking cracks—and of the numerically powerful Afro-Asian group.

In "Global Strategy" the author has made a valiant effort to trace in a comprehensive form the evolution of war and strategy up to the present day. He has achieved near success, but the average reader must feel mental indigestion in an acute form by the time he reaches the final pages. Compression and condensation are the essence of journalism. But in books of this calibre they can hardly be excused.

The pages devoted to an analysis of the shape that the armed forces will take in the future are interesting and acceptable. There can be little criticism of the arguments put forward and the conclusions reached.

Very pleasant is the phrase "A certain complexity characterises the search for strategic principles due to the fact that we do not know what kind of war we shall be called upon to fight." This is certainly a masterpiece of British meiosis. Listening in recent months to the statements of leading men in many spheres the utter confusion that exists in regard to this vital matter is fully apparent. The Defence White Paper, in spite of many failings, does at least bring a wholesale element of common sense into the discussion. "Global Strategy" is a brave book, and if it is possible to study it at leisure, will be found to be rewarding.—P. B. JOUBERT.

TECHNICAL ASPECTS OF SOUND. *Volumes I & II edited by E. G. Richardson. Elsevier Publishing Co., London. 1953-1957. 544 pp. and 412 pp. respectively. Illustrated. 70s. each.*

The publication of the second of these two volumes has completed a very useful source of information on a subject which is becoming increasingly important in the field of aeronautics.

The books cover all aspects of sound including generation, propagation, absorption, detection, measurement, reproduction, musical instruments, recording, ultrasonics, aircraft noise, speech and hearing. There is much material that is not of direct interest to the aeronautical engineer but this is not surprising since the volumes are intended for "advanced students, research workers and industrialists" (presumably in the field of acoustics). However, it is better to have full coverage than gaps. Each subject has been written by a leading authority in that particular field and a uniformly high standard is maintained. The lists of references to original papers at the end of each chapter is to be commended and will be appreciated, especially by the research worker and those requiring fuller information.

The production of the book is excellent and the type and lay-out clear to read and easy to follow. The only criticism is the Index—it could be fuller. In fact there are only about twice the number of pages listed in the Index as there are in the Contents! Several items appear two or three pages in front of the listed page, and a lot of page turning would be saved if fuller use was made of indicating the context when an item occurs in several places in the book. Finally, there is an anomaly: the word "phon" is not indexed but the relationship between the phon and the decibel is given twice (Figs. 67 and 114).

The two volumes can be recommended to all whose work involves sound whether it be noise field investigations, silencing or ultrasonic crack detection. However, the price of 70s. per volume is high, especially if part of the contents will never be used.

Perhaps a future edition will include material on the effect of noise on structures and the nuisance effects of noise on the population.—J. TINKLER.

PRINCIPLES OF GUIDED MISSILE DESIGN (*Aerodynamics, Propulsion and Structures*). *E. A. Bonney, M. J. Zucrow and C. W. Besserer. Van Nostrand, Princeton, 1956. 595 pp. Illustrated. 75s.*

This second volume in the series follows the same pattern as the first (reviewed in the June 1956 JOURNAL) in using a different author for each of the main Divisions of the book. The standard of printing and illustration is again good, and the subject matter forms a valuable general text for technical workers and military users in the missile business. The Aerodynamic Chapters describe in mainly qualitative terms the characteristics of the principal components of typical missiles as they affect the aerodynamic forces, before going on to a simple treatment of dynamic behaviour. There follows a description of wind tunnel, ballistic range and free flight test techniques and a discussion of some aerodynamic effects during the launch and boost stages. Throughout there is a tendency to avoid any quantitative treatment, frequent emphasis on ram-jet configuration, due no doubt to the author's association with the Talos project at the Applied Physics Laboratory, and an extremely perfunctory mention of such important aspects as wing-body interference, heat transfer at very high Mach numbers or the dynamic stability characteristics of twist-and-steer configurations. One suspects that the author has been severely handicapped by close association with the security classified details of a military project, but there seems little excuse or reason for the fantastic bibliography of 525 references, other than a desire to prove, by weight of numbers, that N.A.C.A. has almost a monopoly of supersonic aerodynamic knowledge! The author seems to have been troubled by potential sins of omission; he mentions every aspect of his subject, however briefly, and pads an otherwise well-chosen presentation with vague generalisation. One feels that the influence of the Editor of the series is weakening rapidly, allowing a noticeable difference in the treatment of the first two Divisions, for, by contrast with Aerodynamics, the Propulsion Chapters give a detailed exposition of the fundamental thermodynamic and aerodynamic principles which govern the performance of jet and rocket engines. The presentation is in a form suitable for engineering students, with quantitative examples of considerable practical interest to the propulsion system designer. There is throughout the chapters on turbo-jet, ram-jet and rocket engines, a pleasing clarity of style and a notably successful effort to define and illustrate the interdependence of the basic engine design and performance parameters.

The third section of the book covers design criteria, environmental conditions and reliability concepts. There is a wealth of information on the properties of materials used in missile construction and on the typical environment

requirements they have to meet, but not much advice on appropriate design methods. It is interesting to note that, from the vibration and shock standpoint, truck transportation ranks as the least desirable method of shipping missiles, while shunting operations on railways spoil an otherwise fairly smooth ride. The final chapters discuss component layout and assembly, composite design and manufacturing problems. The ever-present subject of reliability is allotted about 3½ per cent of the total reading matter which no doubt reflects the designers' current ability to increase this much prized feature of missile design.—W. H. STEPHENS.

MISSION COMPLETED. *By Air Chief Marshal Sir Basil Embry. 350 pp. Methuen. 25s.*

When Sir Basil Embry left No. 2 Group at the end of the war, his officers made him a presentation in defiance of the unwritten law of the Service. When he ceased to be A.O.C.-in-C. Fighter Command in 1953, his officers attached ropes to his car and hauled him along the steep drive of Bentley Priory. When he left S.H.A.P.E. at the end of 1955, the French authorities named the sports stadium at Fontainebleau after him in acknowledgment of the work he had done to create it. All these things were tokens of admiration for an officer who never pulled his punches in a fight, who never let himself get out of training for a fight, who took endless trouble to find out how the fight could best be fought and sometimes took the law into his own hands so that the fight might be well fought.

None of us who saw Basil Embry at work doubted for a moment that he enjoyed every minute of it while there were battles to fight and things to be got done. Only when he was immured like a monk in the cloisters of S.H.A.P.E. and expected to go through the motions of organising an international air defence without the power to shake up the constituent parts and put some life into them, did his footwork lose some of its spring, his punches some of their power and his challenging spirit some of its puckish delight in cutting a way through the tangles of diplomacy, obstruction, prejudice and dilatoriness. At last he was indeed frustrated. It was the first time in his 35 years of service in the R.A.F. And that experience makes nonsense of the title of his book.

He went off to New Zealand to farm with his sons, disappointed of success in his last battle for a close-knit, uniformly trained, centrally controlled European air defence force so amenable to S.H.A.P.E.'s staff work that it would swing into action with the precision of a perfect machine at the drop of a Russian hat—or something worse. Perhaps it was an act of one-eyed political optimism to set the ebullient Embry in the quiet quadrangles of Fontainebleau and expect him to adapt his impatient dance to the slow, cautious, sometimes suspicious perambulations of the statesmen and civil servants and Service chiefs of half a dozen nations. Perhaps it was an attempt that failed to let the well-known Embry shock tactics loose on a situation which undoubtedly needed a more urgent sense of realism.

Tortuous ways were never his line of country. He had always said what he meant and driven straight for what he believed was right. One of the weaknesses of his book, generous enough in many ways, is that it never allows anybody who disagreed with him to be proved right in the end. That magnificent self-assurance was, of course, the spring and fount of his drive and initiative. He always took pains and saw that his subordinates took pains to discover the evidence on which conclusions could be formed. He worked just as hard to arrive at solutions. Having found them he endowed them with the force of articles of faith, opposition became heresy and nothing was allowed to divert him.

He presents the most revealing examples of this temperament in this book. In 1940 when, as a wing commander he was stationmaster at Wittering and Beaufighters occasionally overshot the 1,400 yds. grass runway out on to the Great North Road, he grubbed up 1,500 trees, extended the runway to the satellite field three miles away and then buried ordinary cable to serve the runway lights—all without authority. Works and buildings were horrified, especially about that cable. "Whom will I electrocute?" he asked. And when the engineer said: "Most probably one of my maintenance men," he assured him that one engineer a week would be acceptable to save one air crew a month.

Earlier still, he had taken on himself to fit extra guns on the Blenheim. He had the excuse that he had seen "Bert" Harris fit unorthodox equipment in the Vernons in Iraq. In India, he had got his D.S.O. as a squadron leader, for taking action against the Wazirs on his own initiative when he was unable to make contact with the commanding general. Later in the war, as an air vice-marshal, he set up his own model-making section to help in briefing crews as to how to find and approach their targets, after H.Q. had refused authority. He made his own ground trainer for air gunners and obtained a motor from the makers to work the turret by quoting an Air Ministry authority he had not got.

Short cuts for good causes he was generally unable to resist. His officers and men saw what results he got and soon were glad to join him in making things hum. Best of all, he shared with them the risks in the air of all that he planned and contrived on the ground. Right on to the end of the war he was flying with his squadrons, wearing the rank of wing commander, carrying the identity disc of a genuine Wing Commander Smith and having his underclothes marked with the same *nom de guerre*. Officers and men could be overworked and made to step lively in that spirit, especially when they could see their squadron commander or stationmaster or A.O.C. putting higher authority in the proper place if efficiency demanded that liberties be taken. Embry himself enjoyed that too. His book makes it clear that, like Jack Horner, he knew he was a good boy. His men knew also that he was quite capable of bullying the civil servants, even right up in the Treasury, on their behalf.

He wanted action from above and below. He brought zest and ingenuity and a lively skill in improvisation to the jobs he had to do. He had relatively little practice in the exercise of tolerance, patience and the arts of diplomacy and, hard though he tried at S.H.A.P.E. to get results by the gentle and modest approach, no amount of good resolution could long suppress the old thrusting, energetic Adam. He did at least once send a senior French officer to order a dilatory French works and buildings official to sign a contract for work to be done. I have no doubt that like spring in Oklahoma, he was bursting out all over the place when the powers decided to take this uncomfortably busy boy out of N.A.T.O.s slow nuclear reactor before his mission was completed.—E. COLSTON SHEPHERD.

AIRCRAFT OF THE ROYAL AIR FORCE 1918-57. *Owen Thetford. Putnam, London, 1957. 528 pp. Illustrated. 50s.*

Students of military aircraft development in Britain will welcome Owen Thetford's new book. Written by an enthusiastic collector of information it is excellent value for money. It contains a small but nourishing helping of information on the operational life of each of some three

hundred basic types of aeroplane which have served with the Royal Air Force in the period under review, together with about two hundred line-drawings of a high standard of accuracy in almost every respect. The book suffers from one or two irritating inconsistencies but, no doubt, these will be ironed out where possible in a second edition. Some of the wartime aircraft are dealt with in considerably more detail where there are many variations of a particular type.

O. G. Thetford was one of those who, during the late War, started the present passion for detail and accuracy in this field of knowledge and, if he has made errors, they are chiefly of omission but finding fault with his work is one of the finer arts. He clearly does not intend to be caught out in his facts. One unique feature of the book is a list of the squadrons which were equipped by each aircraft described. Squadron Historians will find much of interest therein. To argue that this history is incomplete would be pointless. The author has clearly stated his aims in his Introduction and has achieved a resounding success in painting a background of development in satisfying detail of the ancestry of the modern air weapons-system. The opening words are somewhat sad, having been written some months ago—"Now that the Royal Air Force has come to be recognised as Great Britain's first line of defence. . . ." For how long?—A.S.C.L.

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750 The research airplane—past, present and future. W. C. Williams and H. M. Drake.

751 Airline technical requirements planning. R. D. Kelly.

Reports

AERODYNAMICS

Boundary Layer

Wind-tunnel and flight investigations of the use of leading-edge area suction for the purpose of increasing the maximum lift coefficient of a 35° swept-wing airplane. C. A. Holzhauser and R. S. Bray. N.A.C.A. Report 1276. 1956.

Wind tunnel and flight tests were made to evaluate the lift characteristics and suction requirements of a 35° swept-wing aeroplane with a leading edge area-suction boundary layer control installation.—(1.1.5.1).

Compressible Flow—*see also* Wings and Aerofoils

Transonic flow past cone cylinders. G. E. Solomon. N.A.C.A. Report 1242. 1955.

Experimental results are presented for transonic flow past cone-cylinder, axially-symmetric bodies. The drag coefficient and surface Mach number are studied as the free-stream Mach number is varied and, wherever possible, the experimental results are compared with theoretical predictions. Interferometric results for several typical flow configurations are shown and an example of shock-free supersonic to subsonic compression is experimentally demonstrated.—(1.2.2).

Theoretical calculations of the pressures, forces, and moments at supersonic speeds due to various lateral motions acting on thin isolated vertical tails. K. Margolis and P. J. Bobbitt. N.A.C.A. Report 1268. 1956.

Velocity potentials, pressure distributions, and stability derivatives have been derived by use of supersonic linearised theory for families of thin isolated vertical tails performing steady rolling, steady yawing, constant sideslip, and constant lateral acceleration motions. Vertical tail families (half-delta and rectangular plan forms) are considered for a broad Mach number range. Also considered are the vertical tail with arbitrary sweepback and taper ratio at Mach numbers for which both the leading edge and trailing edge of the tail are supersonic and the triangular vertical tail with a subsonic leading edge and a supersonic trailing edge. End-plate effects for several of the derivatives are included.—(1.2.3.1 × 1.8.1.2 × 1.6.1).

Flight determination of drag of normal-shock nose inlets with various cowling profiles at Mach numbers from 0·9 *to* 1·5. *R. I. Sears et al. N.A.C.A. Report* 1281. 1956.

External drag data are presented for normal shock nose inlets N.A.C.A. 1-series, parabolic, and conic cowling profiles. The tests were made at an angle of attack of 0° by using rocket-propelled models in free flight at Mach numbers from 0·9 to 1·5. The Reynolds number based on body maximum diameter varied from $2{\cdot}5 \times 10^6$ to $5{\cdot}5 \times 10^6$.—(1.2.2).

Intensity, scale and spectra of turbulence in mixing region of free subsonic jet. J. C. Laurence. N.A.C.A. Report 1292. 1956.

The intensity of turbulence, the longitudinal and lateral correlation coefficients, and the spectra of turbulence in a 3·5 inch diameter free jet were measured with hot-wire anemometers at exit Mach numbers from 0·2 to 0·7 and Reynolds numbers from 192,000 to 725,000.—(1.2.2).

The linearized subsonic flow about symmetrical nonlifting wing-body combinations. J. B. McDevitt. N.A.C.A. T.N. 3964. *April* 1957.

A theory is presented for calculating the linearised subsonic flow about symmetrical, non-lifting wing-body combinations. The wing is represented by a planar distribution of sources and the required boundary condition of tangential flow at the body surface is satisfied by placing along the body centre line axial distributions of sources and multipoles.—(1.2.1.1).

Control Surfaces—*see* Wings and Aerofoils

Fluid Dynamics—*see* Wings and Aerofoils

Internal Flow—*see also* Testing and Instruments

*Some aspects of compressor stage design. J. F. Louis and J. H. Horlock. C.P.*319. 1957.

This deals first with the direct problem of the performance of given compressor stages and indicates how the blade sections of various designs approach the stall point. A method is then presented which combines the solutions of the indirect and direct problems. This method enables a designer to determine stages which will satisfy the imposed design conditions and to predict their off design performance up to the stalling point.—(1.5.2).

Analyse générale de l'écoulement subsonique dans un compresseur hélico-centrifuge. M. Costedoat et al. O.N.E.R.A. Publication No. 86.

Une étude expérimentale de l'écoulement dans un compresseur hélicocentrifuge, effectuée à régime moyen (rapport de pression $\bar{\omega}=1{\cdot}6$; nombre de Mach à la sortie de la roue $M_{c_2}=0{\cdot}6$), a permis de localiser et d'évaluer certaines causes de pertes. Outre quelques enregistrements de la pression instantanée à la paroi, les mesures comportent des relevés "moyens", donnés par des prises statiques et des sondes spécialement étalonnées, et qui semblent rester significatifs aux régimes de fonctionnement étudiés, pour lesquels les pulsations de la vitesse sont relativement faibles (de l'ordre de 10%).—(1.5.2.2).

*Uber den Kompressibilitätseinfluss bei ebenen Schaufelgittern starker Umlenkung. K. Oswatitsch and I. Ryhming. D.V.L. Bericht Nr.*28. *March* 1957.—(1.5.3.2).

Loads—*see* Compressible Flow and Wings and Aerofoils

Stability and Control—*see also* Compressible Flow

A method of calculating the short-period longitudinal stability derivatives of a wing in linearised unsteady compressible flow. K. W. Mangler. R. & M. 2924. 1957.

A method is developed for the calculation of the pressure distribution and the aerodynamic forces and moments on a wing performing harmonic pitching and heaving oscillations. The calculation is based on the assumption of inviscid potential flow without shock waves and is restricted to small incidence, so that the linearised theory is valid.—(1.8.2.2).

A collection of data for zero-lift damping in roll of wing-body combinations as determined with rocket-powered models equipped with roll-torque nozzles. D. G. Stone. N.A.C.A. T.N. 3955. *April* 1957.

Zero lift damping in roll data have been collected from experimentally determined results through high subsonic, transonic, and low supersonic speeds by a torque nozzle forced roll technique utilising rocket-propelled models. These collections of data show the effects of wing plan form and aerofoil section and, qualitatively, the effects of wing aeroelasticity.—(1.8.1.2).

Effects of fuselage nose length and a canopy on the static longitudinal and lateral stability characteristics of 45° *sweptback airplane models having fuselages with square cross sections. B. M. Jaquet and H. S. Fletcher, N.A.C.A. T.N.* 3961. *April* 1957.

Results are presented of an investigation of complete models (fuselage fineness ratio varied from 7·41 to 10·18) over an angle of attack range of -10° to 32°. The effects of the canopy and wing on the tail contribution to the static longitudinal and static directional stability characteristics were determined for a fuselage of fineness ratio 9·26. Data were also obtained with the fuselage nose

blunted for a complete model originally having the pointed nose fuselage of fineness ratio 9·26. Data through a sideslip angle range of -24° to 24° were obtained at a few angles of attack.—(1.8.1.2×1.8.2.2).

THERMO-AERODYNAMICS

The erosion of meteors and high-speed vehicles in the upper atmosphere. C. F. Hansen. N.A.C.A. T.N. 3962. *March* 1957.

Analytic relations for velocity, deceleration, size, and relative magnitude of luminosity of meteors are derived in parametric form. Comparison of the theory with observed meteor behaviour indicates that a large fraction of the atmospheric bombardment energy is used in eroding meteor material. Erosion from large, high-speed vehicles in free-molecule flow is calculated and the mass loss is found negligible.—(1.9×24).

WINGS AND AEROFOILS

The calculation of the pressure distribution over the surface of two-dimensional and swept wings with symmetrical aerofoil sections. J. Weber. R. & M. 2918. 1956.

A simple method is described for calculating the pressure distribution on the surface of a thick two-dimensional aerofoil section, at any incidence, in incompressible potential flow. It is particularly suitable for practical applications, since knowledge of the section ordinates only is required. A complete derivation of the theory is given including a detailed discussion of the approximations made and their effect on the accuracy of the results.—(1.10.1.1×1.4.1×1.6.1).

The calculation of the pressure distribution on thick wings of small aspect ratio at zero lift in subsonic flow. J. Weber. R. & M. 2993. 1957.

The method of expressing the velocity increment over aerofoils directly in terms of the section ordinates is extended to cover also straight and swept wings of finite aspect ratio. The wings considered are untapered in plan form but may be tapered in thickness.—(1.10.1.2×1.6.1).

*Increase in lift for two- and three-dimensional wings near the ground. R. M. Licher. Douglas Report No. SM-*22615. *October* 1956.

The effect on the lift of a wing near the ground is approximated theoretically by replacing the ground with an image wing and by representing both real and image wings by networks of finite strength bound and trailing vortices.—(1.10.1).

The proper combination of lift loadings for least drag on a supersonic wing. F. C. Grant. N.A.C.A. Report 1275. 1956.

Lagrange's method of undetermined multipliers is applied to the problem of properly combining lift loadings for the least drag at a given lift on supersonic wings. The best combination of four loadings on a delta wing with subsonic leading edges is calculated as a numerical example.—(1.10.1.2×1.2.3.1).

An investigation at low speed of the flow over a simulated flat plate at small angles of attack using Pitot-static and hot-wire probes. D. E. Gault. N.A.C.A. T.N. 3876. *March* 1957.

Results are presented from Pitot-static and hot wire anemometer surveys of the low-speed flow about a simulated flat plate for angles of attack of 2°, 4°, and 6°. Measurements were obtained for a Reynolds number of 4×10^6.—(1.10.2.1).

Preliminary data at a Mach number of 2·40 *of the characteristics of flap-type controls equipped with plain overhang balances. J. N. Mueller and K. R. Czarnecki. N.A.C.A. T.N.* 3948. *March* 1957.

The preliminary results of an investigation to determine the aerodynamic characteristics of plain overhang balances on flap-type controls are presented. The values of section hinge moment, pitching moment, normal force, and chord force as a function of flap deflection and angle of attack for a basic wing equipped with flaps of 38, 60, and 82 per cent balance are included. Some effects of gap size are shown for the flap of least balance.—(1.10.2.1×1.3.4).

HELICOPTER AERODYNAMICS—*see* REFERENCE LITERATURE

TESTING AND INSTRUMENTS—*see also* FLIGHT TESTING AND SCIENCE—GENERAL

*Instrumentation used in measurement of the three dimensional flow in an axial flow compressor. J. H. Horlock. C.P.*321. 1957.

Measurements of total pressure, static pressure and yaw angle between the blade rows of an axial flow compressor have been made with a variety of previously calibrated instruments and the results of these investigations are compared.—(1.12.5×1.5.2.1).

Elevated stagnation temperature and strain gauge balances in the instrumentation of a supersonic wind tunnel. G. P. Tonkin. AGARD Report 15. *February* 1956.

The work leading up to, and the method of production of, a strain gauge for use in a supersonic tunnel of stagnation temperature greater than 200°C is described. It is a wire and ceramic gauge which can be stored in plain grid form, and its use has afforded successful force and moment measurements. The balances and their design are also described, with references to other auxiliary services necessary in such a tunnel. Presented at the Eighth Meeting of the Wind Tunnel and Model Testing Panel, held from 20th to 25th February 1956 in Rome, Italy.—(1.12.6.2).

Design and construction of wind tunnel models. J. J. Muncey and D. M. Pote. AGARD Report 20. *February* 1956.—(1.12.1×4).

Mach number measurement in high-speed wind tunnels. J. A. F. Hill et al. AGARDograph 22. *October* 1956.

Mach number measurement in the empty tunnel, at local flow points around a model and in the presence of wall interference is discussed. Sources of errors are discussed and certain procedures recommended.—(1.12.1).

Fluctuations and hot-wire anemometry in compressible flows. M. V. Morkovin. AGARDograph 24. *November* 1956.

The problem of extracting information from a heated thin wire cooled by an unsteady compressible flow is treated. Empirical evidence on heat transfer from thin wires at high speeds is analysed. Procedure for the different speed ranges are outlined and probable accuracy discussed. Parallel procedures for mean-flow measurements are also given.—(1.12.6.3).

AEROELASTICITY

Aeroelastische Aufgaben des Flugzeugbaus. H. G. Küssner. Max-Planck-Institut Report 14. 1957.—(2).

DESIGN AND CONSTRUCTION

See MATHEMATICS AND AERODYNAMICS—TESTING AND INSTRUMENTS

AIRCRAFT OPERATION

Measurement and suppression of tension waves in arresting gear rope systems. J. M. N. Willis et al. R. & M. 2981. 1957.

Experiments were made to measure the effect of the tension waves which are induced in an arresting gear rope system after engagement, and to try out means of suppressing these waves. Rope tensions were recorded for tests covering a range of entry speeds up to 117 knots with a test vehicle weight of 5,400 lb. and up to 151 knots at a weight of 2,450 lb. It is shown that the amplitude of the tension waves becomes relatively greater with increase of entry speed and reaches very serious proportions at the maximum speeds obtained. The use of resilient rope anchorages has resulted in the suppression of the tension waves to a large extent, reductions in peak tensions of up to 30 per cent having been achieved.—(5.5).

Factors affecting the field length of STOL aircraft. G. W. Johnston. AGARD Report 81. *August* 1956.

Some consequences of extending existing short field aircraft to the STOL class are described qualitatively. Only the

performance implications as reflected by the requirement of operating the aircraft from a 500 foot field are discussed. For this note STOL aircraft are defined as those which can land or take-off over a 50 ft. obstacle in 500 ft.

AVIATION MEDICINE

The approximation of the response of the human torso to large rapidly applied upward accelerations by that of an elastic rod and comparison with ejection seat data. J. L. Hess. Douglas Report No. ES 26472. *November* 1956.

When the human body is subjected to very rapidly applied accelerations, the accelerations at points of the body can be considerably larger than the maximum value of the applied acceleration. This paper considers the case when the acceleration is applied along the line of the spine from seat to head as in ejection from aircraft and attempts to approximate the motion of the human torso under these conditions by that of an idealised, one-dimensional, visco-elastic structure. The simple case of a homogeneous elastic rod is discussed in detail and its predictions compared with ejection seat data. The extensions to more complicated visco-elastic structures are discussed. It is concluded that the elastic rod is a fairly good first approximation, but that it is not sufficiently exact to be used in making quantitative predictions. It is also concluded that more complicated structures will require more and better data for their evaluation.—(9).

ELECTRONICS

*The losses in series and shunt voltage regulators. I. G. Scott and W. F. L. Sear. A.R.L. Note I.*59. *September* 1956.

A general treatment is given of the losses occasioned in series and shunt regulators and a comparison of the regulators is made on this basis.—(11).

*Electronically stabilised voltage regulators for an analogue computor. I. G. Scott and W. F. L. Sear. A.R.L. Note I.*60 *October* 1956.

Various types of high performance voltage stabilised power supplies are considered. A generally applicable design procedure using proven electronic techniques is evolved and applied to the particular case of a power unit for use with a general purpose analogue computer.—(11).

FLIGHT TESTING

*Design of total temperature probes. D. H. Henshaw and D. F. Daw. N.A.E. LR-*184. *January* 1957.

Procedures are presented for the design of total temperature probes using bare wire thermocouples. Detailed consideration is given to the errors arising from convection, velocity, radiation, conduction and thermal lag. The procedures are applied to the design of three total temperature probes suitable for the measurement of air temperature from ground installation, low speed aircraft and high speed aircraft respectively.—(13 × 1.12).

*Description of the spray rig used to study icing on helicopters in flight. D. L. Bailey. N.A.E. LR-*186. *January* 1957.

The spray rig used to study icing on helicopters in hovering flight is described. Details of operation, instrumentation and the calculated performance are given.—(13 × 24).

FUELS AND LUBRICANTS

Untersuchungen und Entwicklungsarbeiten zur motorischen Prüfung von Schmierölen. G. Spengler and H. Gemperlein. D.V.L. Bericht No. 25. *April* 1957.—(14.2).

HYDRODYNAMICS

*Development of a sensitive rotational viscometer. E. H. Dudgeon and W. C. Michie. N.R.C. Report No. MT-*34. *January* 1957.

A sensitive co-axial rotational viscometer has been designed incorporating certain features to make it especially suitable for use with low viscosity non-Newtonian suspensions. The outer cylinder can be rotated over a considerable range of speeds and the inner cylinder is mounted in hydrostatic air bearings for increased sensitivity. A lower guard plate is incorporated to eliminate end effect with Newtonian fluids. Different combinations of outer and inner cylinders may be mounted to permit accurate measurement at shear rates up to 3,000 sec.$^{-1}$. Viscosities as low as 1 centipoise can be measured conveniently.—(17.1).

MATERIALS

Contribution a l'étude des propriétés et des modes de décomposition de la phase protoxyde de fer. R. Collongues. Pubs. Sc. et Tech. No. 324. 1957.—(21.1).

Application de la micrographie électronique a l'étude de certains aspects de la surface des cristaux et de la nature des joints intergranulaires dans le cas de l'aluminium. P. Bussy. Pubs. Sc. et Tech. No. 325. 1957.—(21.1).

High-resolution autoradiography. G. C. Towe et al. N.A.C.A. Report 1243. 1955.

This investigation was made to adapt wet-process autoradiography to metallurgical samples to obtain high resolution of segregated radioactive elements in microstructures. Results are confined to development of the technique, which was perfected to a resolution of less than 10 microns. The radioactive samples included carbon-14 carburised iron and steel, nickel-63 electroplated samples, a powder product containing nickel-63, and tungsten-185 in N-155 alloy.—(21.6.2).

*Preliminary investigation of the effect of surface treatment on the strength of a titanium carbide-*30 *per cent nickel base cermet. L. Robins and E. M. Grala. N.A.C.A. T.N.* 3927. *February* 1957.

Specimens of a nickel-bonded titanium carbide cermet were given the following surface treatments: (1) grinding, (2) lapping, (3) blast cleaning, (4) acid roughening, (5) oxidising, and (6) oxidising and refinishing. Room temperature modulus of rupture and impact strength varied with the different surface treatments. Considerable strength losses resulted from the following treatments: (1) oxidation at 1,600°F for 100 hours, (2) acid roughening, and (3) severe grinding with 60-grit silicon carbide abrasive. The strength loss after oxidation was partially recovered by grit blasting or diamond grinding.—(21.3.1).

A study of the "toss factor" in the impact testing of cermets by the Izod pendulum test. H. B. Probst and H. T. McHenry. N.A.C.A. T.N. 3931. *February* 1957.

The test method presented shows that the "toss energy" contributed by the apparatus for brittle materials is negligible. The total toss energy is considered to consist of two components, (*a*) recovered stored elastic energy and (*b*) kinetic energy contributed directly by the apparatus. The results were verified by high-speed motion pictures of the test in operation. From these photographs, velocities of tossed specimens were obtained and toss energy computed. In addition, impact energies of some titanium carbide base cermets and high temperature alloys, as measured by the low-capacity Izod pendulum test, compare well with impact energies measured by the N.A.C.A. drop test.—(21.3.1).

An investigation of high-temperature vacuum and hydrogen furnace brazing. W. E. Russell and J. P. Wisner. N.A.C.A. T.N. 3932. *March* 1957.

The vacuum and the hydrogen brazing of four heat-resistant alloys with two types of high-temperature brazing alloy were investigated. The effect of time at various brazing temperatures on the 1,200°F shear strength of joints and on the base-metal tensile strength and elongation was also studied. Brazing techniques for alloys that can be age-hardened and that contain titanium and aluminium in a vacuum as well as in dry hydrogen were evaluated.—(21.2.1).

MATHEMATICS

Résolution de divers problèmes du type Stokes-Beltrami posés par la technique aéronautique. P. Brousse. Pubs. Sc. et Tech. No. 323. 1956.

L'auteur étudie une classe de problémes elliptiques singuliers intervenant dans plusieurs questions de la Mécanique des structures et de la Mécanique des fluides. Les théorèmes d'existence et d'unicité exigent que les données et la solution

possèdent des propriétés particulières; la solution, définie comme limite, est susceptible de plusieurs représentations qui en facilitent l'étude. La théorie est illustrée par de nombreuses applications à des domaines particuliers conduisant à des propriétés intrinsèques remarquables et à des résultats utilisables dans la technique aéronautique.—(22).

Formeln und Tabellen für ein den Hankel'schen Zylinderfunktionen verwandtes Integral. G. v. Gorup. Max-Planck-Institut Report 15. 1957.—(22).

Studies on the acceleration of a body from rest. Part I. The approximate constancy of velocities produced by time-dependent accelerations having equal maximums and operating over equal distances. J. L. Hess. Douglas Report No. ES 26463. *November* 1956.

By analytical calculations for two representative classes of accelerations, by a discussion of the reasonableness of the conclusions for more general acceleration, and by consideration of experimental data, it is shown that, if a body is accelerated from rest through a fixed distance by accelerations having the same maximum value, the final velocities will differ by very little, regardless of the shape of the acceleration against time curve. Conclusions on ejection seat design are drawn from this fact. The result, however, has more general applicability.—(22.2×4.2.1).

MECHANICAL ENGINEERING

*Supports for vibration isolation. W. G. Molyneux. C.P.*322. 1957.

Spring arrangements are described that provide flexible supports of very low stiffness for a limited range of movement. Particular applications of the arrangements for vibration isolation and in other fields are discussed.—(23).

Preliminary metallographic studies of ball-fatigue under rolling-contact conditions. H. R. Bear and R. H. Butler. N.A.C.A. T.N. 3925. *March* 1957.

The metallurgical results produced on balls tested in the rolling-contact fatigue spin rig were studied by metallographic examination. Origin and progression of fatigue failures were observed. These evaluations were made on SAE 52100 and AISI M-1 balls fatigue tested at room temperature (80°F) and 200° to 250°F. Most failures originated sub-surface in shear; inclusions, structure changes, and directionalism adversely affected ball fatigue life. Structures in the maximum shear stress region of the balls of both materials were stable at room temperature and unstable at 200° to 250°F. Failures were of the same type as those in full-scale bearings.—(23.1×31.2.3.1.8).

Stress-life relation of the rolling-contact fatigue spin rig. R. H. Butler and T. L. Carter. N.A.C.A. T.N. 3930. *March* 1957.

The rolling-contact fatigue spin rig was used to test groups of SAE 52100 9/16 inch diameter balls lubricated with a mineral oil at 600,000-, 675,000-, and 750,000-p.s.i. maximum Hertz stress. Cylinders of AISI M-1 vacuum and commercial melts and MV-1 (AISI M-50) were used as race specimens. Stress-life exponents produced agree closely with values accepted in industry. The type of failure obtained in the spin rig was similar to the sub-surface fatigue spalls found in bearings.—(23.1×31.2.3.1.8).

Effect of fiber orientation on ball failures under rolling-contact conditions. R. H. Butler et al N.A.C.A. T.N. 3933, *Feb.* 1957.

The rolling-contact fatigue spin rig was used to test balls of a bearing steel at maximum Hertz stresses of 600,000 to 750,000 p.s.i. The effect of fibre orientation was observed with the ball track restricted to passing directly over the poles, coincident with the equator, or randomly around the ball. The polar areas were found to be weaker in fatigue than the non-polar areas. This resulted in a much greater portion of the failures occurring in the polar areas than would be expected from a homogeneous material. Early failures are discussed.—(23.1×31.2.3.1.8).

METEOROLOGY

see also AERODYNAMICS—THERMO-AERODYNAMICS AND FLIGHT TESTING

A limited correlation of atmospheric sounding data and turbulence experienced by rocket-powered models. H. P. Mason and W. N. Gardener. N.A.C.A. T.N. 3953. *April* 1957.

Atmospheric turbulence as experienced by rocket-powered models and temperature lapse-rate data obtained from rawinsonde soundings have been analysed and compared in 38 cases by using an assumed lapse-rate stability boundary.—(24).

POWER PLANTS

Steady nuclear combustion in rockets. E. Sänger. N.A.C.A. T.M. 1405. *April* 1957.

Astrophysical theory is applied to study possibilities for thermo-nuclear reactions to be used as an energy source for the propulsion of atomic rockets, photon rockets, turbo-jets, and ram-jets.—(27.3×34.1).

Experimental comparison of speed-fuel-flow and speed-area controls on a turbojet engine for small step disturbances. L.M. Wenzel et al. N.A.C.A. T.N. 3926. *March* 1957.

Optimum proportional plus integral control settings for speed fuel-flow control, determined by minimisation of integral criteria, correlated well with analytically predicted optimum settings. Engine response data are given for a range of control settings around the optimum. An inherent non-linearity in the speed area loop necessitated the use of non-linear controls. Response data for two such non-linear control schemes are presented.—(27.1).

Full-scale investigation of several jet-engine noise-reduction nozzles. W. D. Coles and E. E. Callaghan. N.A.C.A. T.N. 3974. *April* 1957.

A number of nozzles which use the mixing interference of adjacent jets for noise suppression were investigated. A method of calculating the limiting frequency affected by this type of suppression nozzle, that is, multiple-slot nozzles, is presented.—(27.1).

Exploratory study of ground proximity effects on thrust of annular and circular nozzles. U. H. von Glahn. N.A.C.A. T.N. 3982. *April* 1957.—(27).

REFERENCE LITERATURE

*Notation for rotorcraft work. A. Armitage. C.P.*314. 1957.

A suggested standard notation for rotorcraft work is presented. The notation is the outcome of study of numerous papers of many sources of origin.—(30×1.11).

FATIGUE

See also MECHANICAL ENGINEERING

*Substantiation of safe fatigue life for rotorcraft. W. A. P. Fisher. C.P.*317. 1957.

A comprehensive system of development and testing to substantiate rotorcraft for fatigue is given.—(31.2.6).

SCIENCE—GENERAL

Optical methods for examining the flow in high-speed wind tunnels. Part I. Schlieren methods. D. W. Holder and R. J. North. Part II. Interferometer methods. G. P. Wood. AGARDograph 23. *November* 1956.

The present state of knowledge concerning the use of schlieren, direct-shadow, and interferometer techniques for visualising and photographing the flow in high-speed wind tunnels is reviewed, including methods in an early stage of development, or useful only in a limited range. Information on light sources and photographic materials is included.—(32.2.4×1.12.1.3).

THERMODYNAMICS

See POWER PLANTS